DEVELOPMENT OF THE FIVE DEGREE-OF-FREEDOM
LINEAR MODEL FOR THE XR-3 SURFACE EFFECT SHIP
AND INVESTIGATION OF THE ROLL BEHAVIOR
OF THE CRAFT IN TURN MANEUVERS

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THESIS

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December 1979

Thesis Advisor: G. J. Thaler

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Development of the Five Degree-of-Freedom Linear Model for the XR-3 Surface Effect Ship and Investigation of the Roll Behavior of the Craft in Turn Maneuvers		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Fuat Ozanturk		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE December 1979
		13. NUMBER OF PAGES 118
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Surface Effect Ship
XR-3 Test Craft
Linear Model
Five Degree-of-Freedom

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1)   S/N 0102-014-6601 |

(20. ABSTRACT Continued)

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1979

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of the craft in turn maneuvers are investigated by both
linear and six degree-of-freedom nonlinear models, and the
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linear model simulations. Some of the parameters of the
craft are investigated for roll motion.

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I.   INTRODUCTION

A.   BACKGROUND

The Surface Effect hybrid type high performance ship has been of great interest recently, and in 1970 the XR-3 test craft was delivered to the Naval Postgraduate School. As seen in [7] Leo and Boncal converted the digital simulation program for the 100-B test craft to represent the XR-3, thus providing a nonlinear model. In [1], Gerba and Thaler have developed a heave-only linear model and further studies were made by Barnes in [2] by developing a two degree-of-freedom linear pitch and heave model representing the XR-3 test craft.

B.   OBJECTIVE

In order to investigate the roll behavior of the XR-3 test craft during turn maneuvers, a five degree-of-freedom linear model is developed in this thesis. Some modifications are made for pitch and heave modes, therefore test of the vertical plane by means of weight removal is reinvestigated and compared with the nonlinear simulation results.

In [3], the roll behavior of the XR-3 and the sidewall sensitivity are studied using a six degree-of-freedom non-linear model. Similar studies are made in this thesis after developing a five degree-of-freedom linear model and comparing with the nonlinear model results. Finally, some modifications are suggested for nonlinear modeling.

II. NONLINEAR XR-3 MODELING FOR FIVE DEGREE-OF-FREEDOM

A. ASSUMPTIONS

The following assumptions and simplifications are used during development of a constant speed XR-3 test craft model:

1. Aerodynamic drag on the forward seal, and superstructure skin friction forces are neglected.

2. Momentum (ram) drag is disregarded for all modes. In other words, it is accepted that the location of the lift fans with respect to the craft C.G. could not affect significantly the roll and pitch stability. Also, air stagnation force in the z-direction is assumed to be negligible.

3. During dynamic response of the craft, only air leakage with constant leakage area at the stern seal is assumed. No other air escape is considered such as possible leakage from sidewalls or bow seal.

4. Plenum pressure and air mass thermodynamics are represented by ideal diabatic processes with the air constant specific heat ratio $\gamma = 1.4$.

5. Effective plenum roof area is developed as a function of craft weight.

6. Planing forces are concentrated at the centroid of the keel longitudinal cross section through the fluid medium.

7. Pitch and roll damping moments due to added mass are included in the craft dynamics, but their contribution to heave motion is neglected.

8.   The thrust forces and all hydrodynamic resistive forces (drag) in the z-direction cancel each other, since at constant speed operation, these forces are in equilibrium. However they might contribute to the moment equations such as pitch moment, but considering their effective moment arms with respect to the C.G. are almost equal to the thrust moment arm, so that their contribution in the moment equations is also neglected.

9.   For seal modeling, vertical resistive forces due to hydrodynamic response are taken into account including corresponding effective wetted seal area.

10.   Simplified craft geometry is used for plenum, buoyancy and seal modeling.

B.   COORDINATE SYSTEM AND SIGN CONVENTIONS

1.   The cartesian coordinate system is used with its origin located on the water line corresponding to the craft center of gravity.

2.   The x-axis lies on the water line with the positive longitudinal displacement being measured forward.

3.   The y-axis lies in the vertical cross section plane with the lateral dislacement being measured positive to starboard.

4.   The z-axis lies in the vertical cross section plane with the positive vertical displacement being measured downward.

5.   z represents heave C.G. displacement measured from the origin (at water line) to the center of gravity.

6. z_s is one of the craft dimensional values measured from the keel to the C.G.

7.   Pitch is the rotational motion about the y-axis, angular pitch displacement is represented by θ, positive pitch angle is measured upward (boat noses up).

8.   Roll is the rotational motion about the x-axis, ϕ angle represents angular roll displacement, positive roll angle is measured to starboard (boat heels to starboard).

9.   Similarly the yaw is the rotational motion about the z-axis, positive yaw is measured in the clockwise direction.

10. Positive roll, pitch and yaw moments are to be defined as the moments in the positive roll, pitch and yaw directions correspondingly.

11. As a reference zero pitch and roll angle provide the x-y plane parallel to the water surface.

The craft coordinate system is shown in figure 1.

C.   SIMPLIFIED CRAFT MODELING AND GEOMETRY

1.   General Simplified Geometry and Dimensions of the XR-3 Test Craft

In figure 1 the sideview simplified geometry of the XR-3 test craft is shown. Also in figure 3 the top view is illustrated. The variables and dimensions in these figures are defined as follows;

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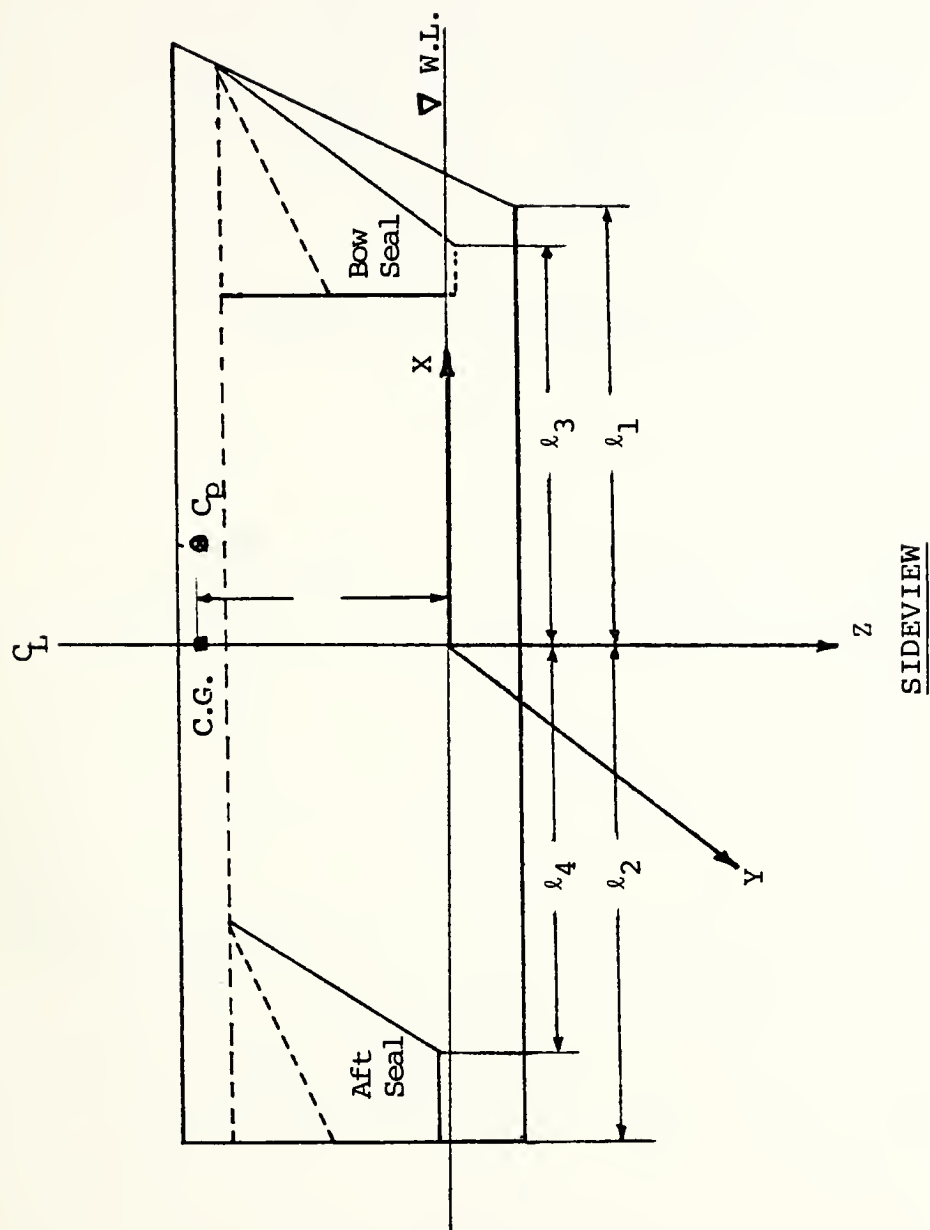
Figure 1. Craft coordinate system and simplified geometry (sideview)

SIDEVIEW

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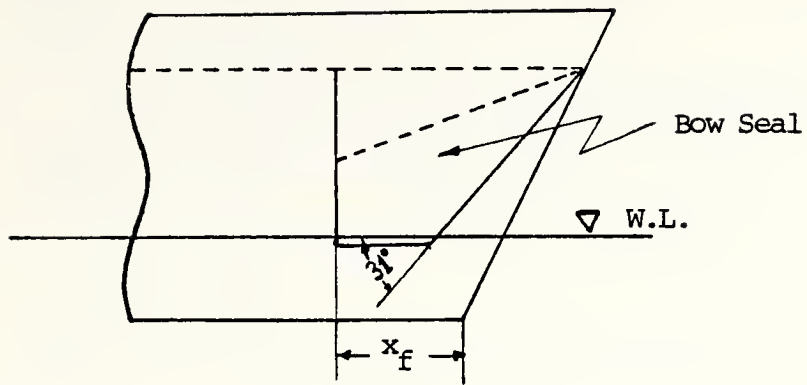
Figure 2. Bow seal geometry
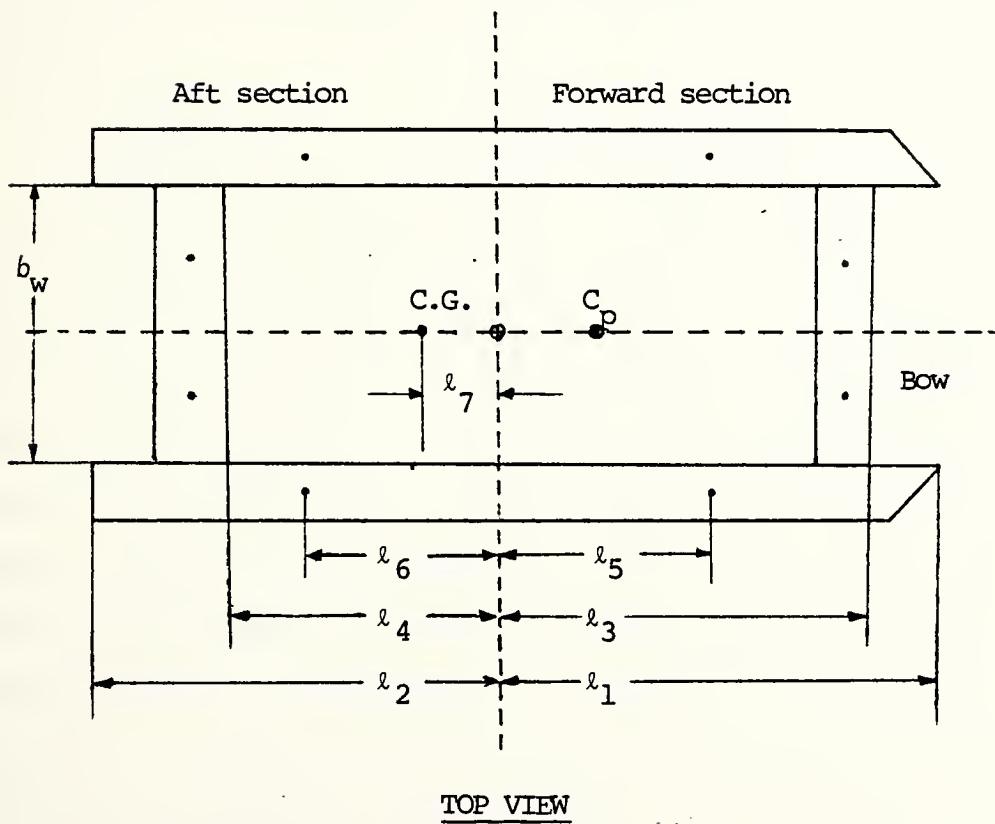
TOP VIEW

Figure 3. Simplified geometry (top view)

ℓ_d = Draft of the craft at center of gravity

C_p = Plenum pressure center (the centroid of the effective plenum area)

ℓ_5, ℓ_6 = The longitudinal distance of the sections' centroids from the C.G. (forward and aft section centroids respectively)

ℓ_3, ℓ_4 = Bow and stern seals front face distances at water level

ℓ_7 = Centroid distance of the planing force effective area

ℓ_1, ℓ_2 = Forward and aft sections sidewall submerged region length.

All craft dimensional values are taken from the XR-3 six degree-of-freedom model scale drawings as indicated in [2] and [3].

2. <u>Sidewalls</u>

As reported in [2], the sidewall modeling is developed from the SIDEWALL subroutine of the 6 DOF computer model. Like craft dimensions, all sidewall dimensions and their related geometric configurations are based on scale model drawings. For simplicity of calculation, the sidewalls are divided into two sections called forward and aft. During dynamic response of the sidewalls, these sections are considered individually with their own centroids, so related calculations can be done easily. Especially, the sidewall modeling is developed in order to determine buoyancy forces and moments. By means of this modeling, the average sidewall width, average draft at section centroid and effective

plenum area are also determined and used extensively in the rest of the calculations.

The sidewall vertical cross sections at the section centroid forward and aft are sketched in figures 4(a) and 4(b) respectively. From these figures, the average forward sidewall width at the buoyancy center is found to be

$$\overline{b}_f = \frac{\ell_f}{2 \tan \beta_1} + b_f \qquad (II-1)$$

where

ℓ_f = Draft at forward buoyancy center

$\tan \beta_1$ = Tangent of the sidewall deadrise angle at the forward buoyancy center

b_f = Sidewall flat surface width at the kell (forward section)

Therefore submerged sidewall volume of the forward section is given as follows

$$V_1 = \overline{b}_f \, \ell_f \, \ell_1 \qquad (II-2)$$

ℓ_f can be formulated as

$$\ell_f = \ell_d - \ell_5 \tan \theta$$

then the small angle approximation $\tan \theta \doteq \theta$ gives

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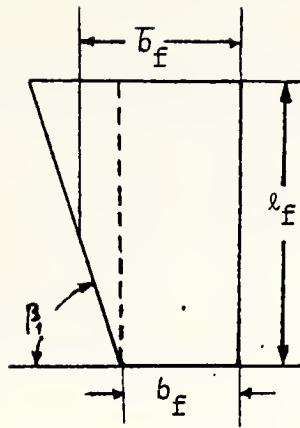
Forward section

Figure 4(a)
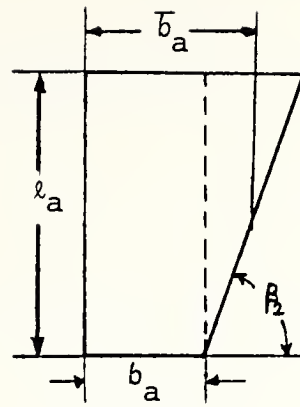
Aft section

Figure 4(b)
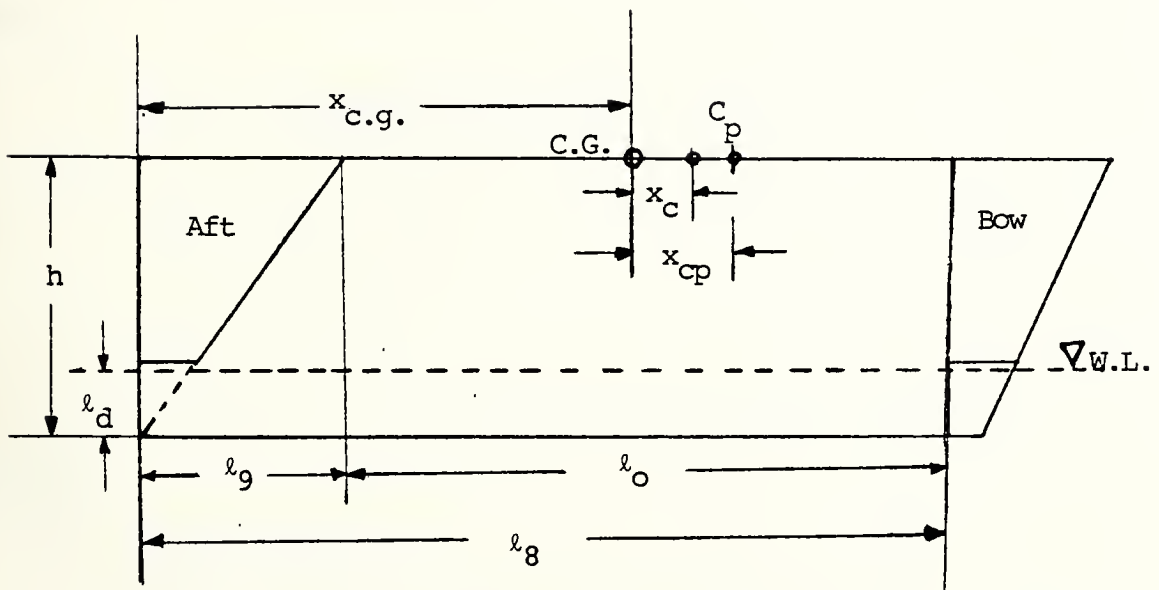
Figure 5. Plenum modeling

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$$\ell_f = \ell_d - \ell_5 \theta \qquad\qquad (II-3)$$

As defined before, ℓ_d draft at C.G. is

$$\ell_d = z_s + z \qquad\qquad (II-4)$$

Similar expressions can be derived for the aft section,

$$\overline{b}_a = \frac{\ell_a}{2 \tan \beta_2} + b_a \qquad\qquad (II-5)$$

where

$\quad b_a$ = sidewall flat surface width at the keel (aft section)

$$V_2 = \overline{b}_a \ell_2 \ell_a \qquad\qquad (II-6)$$

$$\ell_a = \ell_d + \ell_6 \theta$$

Note that ℓ_f, ℓ_a are functions of draft and pitch angle.

3. Plenum Modeling

In [2] plenum modeling is presented including plenum pressure variation due to changing of draft. In the development of a pitch, heave and roll linear model, the simplified plenum geometry and dynamics which were derived by Barnes are considered and used in our plenum dynamics representation.

The variables and dimensions for plenum modeling, as seen in figure 5, are found as

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$$\ell_p = \ell_8 - \ell_9 \left(\frac{\ell_d}{h}\right) \qquad\qquad \text{(II-8)}$$

$$A_b = b_w \, \ell_p \qquad\qquad \text{(II-9)}$$

$$\ell_9 = \ell_8 - \ell_o$$

where

ℓ_p = Length of plenum at the water line

A_b = Effective plenum area

b_w = Lateral distance from one sidewall to another in the plenum region.

ℓ_9, ℓ_8, ℓ_d, ℓ_o and h are all constants related to craft dimensions. Only the effective plenum area A_b varies when the craft draft varies, that means variation of the plenum pressure centroid C_p is forward or backward.

4. <u>Bow and Aft Seals</u>

The seals are an involved additional dynamic system with their own degree of freedom relative to the craft, and they carry little load compared with the other components of the craft. However in the simplified model, the seal motions relative to the craft are neglected.

The assumed seal geometry is shown in figure 2, developed in [2]. Using an appropriate geometric configuration, the seal wetted area is derived as a function of craft draft and pitch angle.

From [2], the width of the wetted surface for the bow seal is;

$$x_f = \frac{\ell_d - \ell_3 \tan \theta}{\sin 31°} \qquad \text{(II-10)}$$

where

$\sin 31°$ = sin of the angle between water surface and the bow seal front face.

The numerator of this ratio represents draft at the bow seal front face.

A similar expression for the stern seal is;

$$x_a = \frac{\ell_d + \ell_4 \tan \theta}{\sin 32°}$$

Multiplying x_f and x_a by b_w, bow and stern seals wetted areas are obtained as follows;

$$A_f = b_w x_f$$

$$A_a = b_w x_a$$

5. Rudder and Propulsion Hydrodynamics

The rudder hydrodynamics is calculated from [4], inserting rudder geometry dimensional values into the fin equations. Actually we are interested in the lateral force (sway) on the rudders for a given rudder order deflection. This dynamic equation is given in [4] as follows;

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$$Y_r = \rho u^2 A_r (1 + \frac{d_s}{h_r}) C_r [\delta_r - (1 + \frac{d_s}{h_r}) \frac{V_h}{u}] \qquad \text{(II-11(a))}$$

where

A_r = Rudder platform area (for one rudder only)

d_s = draft at the stern = $z + z_s - x_r \theta$

h_r = Vertical depth to bottom tip of the rudder

C_r = Rudder lift coefficient

= $\dfrac{2\pi R_a}{R_a + 3}$ (for fully wetted flow regime)

R_a = The rudder aspect ratio

δ_r = Rudder deflection (the sign convention of the rudder is to be positive for port turn)

V_h = $V + x_r r - z_s p$

x_r = longitudinal coordinate of rudder geometric center (always negative value)

V = lateral speed (ft/sec)

r = yaw rate (rad/sec)

In order to simplify the rudder dynamic equation, the following coefficients are defined as

$$C_e = 1 + \frac{d_s}{h_r}$$

$$C_t = \rho u^2 A_r (1 + \frac{d_s}{h_r}) C_r$$

Then equation (II-11(a)) becomes

$$Y_r = C_t(\delta_r - C_e \frac{V_h}{u})$$ (II-11(b))

Let us define z_r to be the vertical coordinate of the rudder from the C.G. to its geometric center, the rudder roll and yaw moments can be calculated from

$$K_r = -Y_r z_r$$ (II-11(c))

$$N_r = Y_r x_r$$ (II-11(d))

During turn maneuvers, the propulsion thrust vector is also deflected according to the given rudder order. Therefore the lateral component of the thrust contributes yaw and roll moments as well as a sway mode, but this diturbance must be considered as a step input to the linear modes with constant magnitude, therefore the total propulsion sway force is

$$Y_{pr} = 2 X_t \sin \delta_r$$ (II-12)

where X_t is the propulsion thrust corresponding to craft speed.

Similarly the roll and yaw moments generated by the propulsion system are

$$K_{pr} = Y_{pr} z_p$$ (II-13(a))

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$$N_{pr} = Y_{pr} x_p \qquad (\text{II-13(b)})$$

where x_p and z_p are the longitudinal and vertical locations of the propeller respectively.

D. DYNAMIC FORCES FOR FIVE DEGREE-OF-FREEDOM MODES

   1. Seal Forces

Considering the seal configuration and dynamics, the pressure difference across the wetted portion of the seal is

$$\overline{P}_b = P_b - P_a$$

where

$$\overline{P}_b = \text{Plenum gauge pressure (lb/ft}^2)$$

$$P_a = \text{Atmospheric pressure}$$

Since the seal is in equilibrium, the vertical hydrodynamic force on the seal is

$$Z_{sf} = - \overline{P}_b A_f$$

$$= - \overline{P}_b \cdot b_w \left(\frac{\ell_d - \ell_3 \theta}{\sin 31°} \right) \qquad (\text{II-14})$$

For the stern seal hydrodynamics, a similar expression can be found as

$$Z_{sa} = - (\overline{P}_b + P_i) \cdot \ell_d \left(\frac{\ell_d + \ell_4 \theta}{\sin 32°} \right) \qquad (\text{II-15})$$

where

> P_i = Additional pressure supplied into stern air bags in order to reduce leakage.

2. Buoyant Forces

The forward section buoyant force is determined from equation (II-2), it is

$$Z_{bf} = - 2 \rho g V_1$$

here ρ is the density of the seawater and g is the gravitational constant.

Finally, the forward and aft section forces are

$$Z_{bf} = - 2 \rho g \left(\frac{\ell_f}{2 \tan \beta_1} + b_f\right) \ell_f \ell_1 \qquad \text{(II-16)}$$

$$Z_{ba} = - 2 \rho g \left(\frac{\ell_a}{2 \tan \beta_2} + b_a\right) \ell_a \ell_2 \qquad \text{(II-17)}$$

3. Planing Forces

In addition to the pitch angle θ, the sidewall flat area at the keel determines the planing effect of the craft. When the craft pitches up, the frontal area (through the fluid medium) causes a lift-drag force in the z-direction.

The planing force, from Reidel's work [3], is;

$$Z_{p\ell} = - \frac{1}{2} \pi \rho A u^2 \sin \theta$$

where

A = flat surface area at the keel

u = speed of the craft

Using the small angle approximation and including the loss coefficient C_{p1} suggested by Barnes in [2], the planing force is redetermined as

$$Z_{p1} = - C_{p1} \pi \rho A u^2 \theta \qquad \text{(II-18)}$$

A similar expression is derived for sidewall dynamics in [4], but in our modelling equation (II-18) is used.

4. Pitch Damping Forces

The sidewalls of the surface effect ship influence moderately heave, pitch and roll modes, so in [4] the hydrodynamic and hydrostatic forces and moments acting on the sidewalls of uniform triangular cross section are derived with particular application to vertical plane motion and lateral motion.

Considering constant speed operation of the craft, neglecting some terms in the equations provided from [4], the vertical force acting on only one sidewall is found as;

$$Z_{sw_1} = A_{33} x_s u q \qquad \text{(II-19)}$$

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where

A_{33} = vertical added mass calculated at the stern

$\quad$ = $(\pi/8)\ \rho\ B_s^2$

B_s = value of sidewall waterline at the sidewall stern

x_s = stern distance from C.G. (negative value)

q = pitch rate (rad/sec).

For the pitch damping moment, the same equation is used by Barnes in [2].

5. Roll Damping Forces

The XR-3 test craft is dynamically similar to 100-B surface effect ship. Therefore we can use dynamic equations calculated in [4] for the XR-3 test craft. The heave-roll damping force for one sidewall can be written as;

$$Z_{sw_2} = - A_{33}\ u\ b_o\ p \qquad\qquad (II-20)$$

In the above equation, b_o is half of the craft width and it must be used (+) for starboard sidewall, (-) for port sidewall.

Similarly the lateral damping force due to sidewall hydrodynamics is

$$Y_{sw_1} = - A_{22}\ u(v + x_s r - z_s p) \qquad\qquad (II-21)$$

here A_{22} is the lateral added mass calculated at the stern, p is the roll rate. A_{22} is calculated from [4], that is

$$A_{22} = \pi/5 \; \rho \; d_s^2$$

6. Plenum Pressure Lift Force

From [2] and [4], the plenum pressure lift force is determined assuming uniform pressure distribution, This is formulated as

$$Z_p = - A_b \bar{P}_b$$

from equations (II-8) and (II-9) follow

$$Z_p = - b_w \bar{P}_b (\ell_8 - \frac{\ell_9 \ell_d}{h}) \qquad \text{(II-22)}$$

E. DYNAMIC PLENUM AIR MASS, PRESSURE EQUATIONS

Assuming constant aft seal leakage area, the leakage flow rate (Q_{out}) is given by Gerba and Thaler for the XR-3 heave only model in [1], then we have

$$Q_{out} = C_n A_\ell (\frac{2 \bar{P}_b}{\rho_a})^{1/2} \qquad \text{(II-24)}$$

where

C_n = Nozzle flow coefficinet

A_ℓ = Leakage area

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ρ_a = Atmospheric air density.

The linearized air flow (Q_{in}) into the plenum is presented in [5] according to the fan properties and calculated in [1] as follows,

$$Q_{in} = n(Q_O - k_p \bar{P}_b) \qquad (II-24)$$

where n is the number of fans supplying the air to the plenum, Q_O is the steady state air flow rate corresponding to steady gauge pressure, k_p is (1/slope) of the $\bar{P}_b$ vs. Q_{in} curve at the equilibrium point.

From equations (II-23) and (II-24), the plenum air flow rate can be written as

$$\dot{M}_b = \frac{dm_b}{dt} = \rho_a(Q_{in} - Q_{out}) \qquad (II-25)$$

The equation (II-25) reveals that if the fan flow rate (Q_{in}) equals to the leakage flow rate (Q_{out}), then the plenum air mass (M_b) is constant.

The absolute plenum pressure is calculated from

$$P_b = P_a \left(\frac{M_b}{V_b \, \rho_a}\right)^{\gamma} \qquad (II-26)$$

In the above equation, V_b is defined as plenum volume and its simplified form is calculated from [1],

$$V_b = (V_n - A_b \, \ell_d) \qquad \text{(II-27)}$$

where V_n is to be the empty plenum volume.

F. NET HEAVE FORCE

The resultant heave force is the summation of the all external dynamic forces, it is

$$Z = Z_{sf} + Z_{sa} + Z_{bf} + Z_{ba} + Z_{pl} + Z_{sw} + Z_p$$

where

$$Z_{sw} = Z_{sw_1} + Z_{sw_2}$$

Z_{sw} also includes a pair of heave buoyancy forces due to roll, but they are in opposite directions. Therefore these stabilizing forces are only taken into account in the roll motion.

G. PITCH AND ROLL MOMENTS

1. Seal Moments

a. Pitch Mode

The seal force is modeled by Barnes in [2] acting on the center of the seal wetted length. The effective pitch moment arms are;

$$\ell_{sf} = \ell_3 - x_f/2 \qquad \text{(for forward seal)} \qquad \text{(II-28)}$$

$$\ell_{sa} = \ell_4 + x_a/2 \qquad \text{(for aft seal)} \qquad \text{(II-29)}$$

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From this follows the forward and aft seal moments

$$M_{sf} = - Z_{sf} \, \ell_{sf} \qquad \text{(II-30)}$$

$$M_{sa} = - Z_{sa} \, \ell_{sa} \qquad \text{(II-31)}$$

where Z_{sf} and Z_{sa} have already been defined.

      b.   Roll Mode

      The flexible seals can contribute little to roll stability. Actually the seal configurations and hydrodynamics are relatively more complex. In [4], the seal roll moments are calculated by combining the roll contribution of all seal elements.

      Considering the seal response, the submerged region of the seal can be calculated and its roll moment contribution can be formulated in the following equations;

$$K_{sf} = - b_w^{\,3}/12 \; \rho \; g \; x_f \tan \phi \qquad \text{(II-30)}$$

$$K_{sa} = - b_w^{\,3}/12 \; \rho \; g \; x_a \tan \phi \qquad \text{(II-31)}$$

      For this modeling, the roll moment arm is considered as $(2/3 \; b_o)$, that is the centroid of the triangle cross section of the submerged portion.

   2. <u>Buoyant Moments</u>

      a.   Pitch Mode

      The pitch buoyancy moments are calculated from equation (II-16) and (II-17) assuming constant moment arms

ℓ_5 and ℓ_6. The pitch buoyancy moments are

$$M_{bf} = - Z_{bf} \, \ell_5 \qquad\qquad (II-32)$$

$$M_{ba} = Z_{ba} \, \ell_5 \qquad\qquad (II-33)$$

b. Roll Mode

As discussed in the heave mode, the effect of the sidewall buoyancy due to the roll is to be a stabilizing moment. From figures 4(a) and 4(b) the buoyancy volume change can be approximated as

$$\Delta V_f = (\frac{b_f + b_w}{2} + \frac{\ell_f}{2 \tan \beta_1}) (\frac{\ell_f}{\tan \beta_1} + b_f) \ell_1 \phi \qquad (II-34)$$

Finally, roll moment is

$$K_{bf} = - 2 \rho g \Delta V_f \qquad\qquad (II-35)$$

Similarly, the aft section roll moment is

$$K_{ba} = - 2 \rho g \Delta V_a$$

3. Planing Pitch Moment

The planing effect due to the sidewall flat area at the keel contributes only pitch motion as follows;

$$M_{pl} = Z_{pl} \, \ell_7$$

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4. Pitch Damping Moment

This is calculated from equation (II-19) as

$$M_{sw} = -2 Z_{sw_1} x_s = -2 A_{33} u x_s^2$$

In the above equation, the factor "2" appears because there are two sidewall sections.

5. Roll Damping Moment

Combining equation (II-20) and (II-21), the roll damping component is

$$K_{sw} = 2 Z_{sw_2} b_o - Y_{sw_1} z_s + K_{wave} \quad (II-37)$$

where K_{wave} represents the additional roll damping term because of vertical wave generation in the roll.

From [3] and [4], K_{wave} is

$$K_{wave} = -32/\pi \, b_o^2 \, B_c \, P \qquad (II-38)$$

Here, B_c is the sidewall vertical added mass given as

$$B_c = \pi/8 \, \rho \, \ell \, \ell_d^2 \, \text{Cotan}^2 \beta .$$

6. Plenum Pitch Moment

From equation (II-22) and defining X_{cp} to be the plenum pressure centroid, the plenum pitch moment is given as

$$M_p = -Z_p X_{cp} = A_b(P_b - P_a) X_{cp}$$

where X_{cp} is calculated as a function of craft draft in [2] as follows;

$$X_{cp} = X_c + (\ell_g \ell_d)/2h$$

$$X_c = \ell_8/2 + X_{c.g.}$$

7. Plenum Roll Moment

The destabilizing static plenum roll moment is generated when the craft rolls to one side. Since the effective plenum pressure centroid shifts laterally to the other side tending to increase rolling of the craft. The plenum roll moment is

$$K_p = A_b(P_b - P_a)(z_s - \ell_d)\phi$$

8. Rudder and Propulsion Roll Moments

These roll moments have already been calculated from equation (II-11(c)) and (II-13(a)).

H. SWAY FORCES

1. Cross Flow Drag (Sidewall)

During the turn maneuver, the cross flow drag is generated acting on the outboard sidewall. The direction of this force is negative while turning to the left.

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Neglecting the lateral drag component inside of the sidewall, the net cross flow drag can be calculated from

$$D_{sw} = -\frac{1}{2} \rho \, \text{sign}(V_r) \, C_d \, V_r^2 \, \ell(\ell_d \pm b_o \phi) \qquad \text{(II-39)}$$

where

$$V_r = v + x_s r - (z_s - \ell_d/2)p$$

$$C_d = \text{cross flow drag coefficient}$$

Considering the outboard surface of the submerged sidewall sections (dead rise angle effect),the lift force in the z-direction can be produced due to the lateral drag deadrise projection. In [4], the importance of the sidewall deadrise angle is mentioned, however at the hydrodynamic section in this reference, the lift component of the drag force has not been derived.

In this modeling, the lift force (Z_d) and lateral drag component is calculated assuming both have the same drag coefficients ($C_d = 1.28$). They are

$$Y_d = D_{sw} \sin \beta \qquad \text{(II-40)}$$

$$Z_d = D_{sw} \cos \beta \qquad \text{(II-41)}$$

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From equation (II-40) and (II-21), the total hydro-dynamic sway force of the sidewall is

$$Y_{sw} = (D_{sw} + Y_{sw_1}) \sin \beta + Y_{sw_1} \qquad \text{(II-42)}$$

2. Centrifugal Force

The centrifugal force acting on the C.G. of the craft is always in the outboard direction during the turn maneuver. Y_c is the centrifugal force, given as

$$Y_c = - m \frac{u^2}{R}$$

R, the turning radius is equal to (u/r), combining this with the above equation gives

$$Y_c = - m u r \qquad \text{(II-43)}$$

a negative sign is used due to the coordinate system sign convention. Since the right turn produces (+) yaw rate, then Y_c is calculated as (-), so outboard sway force is generated for this configuration.

3. Rudder and Propulsion Sway Forces

They are determined from equation (II-11(b)) and (II-12).

The sway forces due to the seals, air plenum and aerodynamic drag are neglected in this modeling.

I. YAW MOMENTS

1. Sidewall Yaw Moment

The sidewall yaw dynamic equations are given in [4]. After some simplification, the net widewall yaw moment is calculated from

$$N_{sw} = N_1 + N_2 + (X_{pw} - X_{sw}) \, b_o \qquad \text{(II-44(a))}$$

where

$$N_1 = 2u(v + x_s r - z_s p)A_{22}\ell(1 - \lambda)$$

$$- \pi/5 \cdot \rho(\ell_d \pm b_o \phi)^2 \ell u(v - z_s p) \qquad \text{(II-44(b))}$$

$$N_2 = - \rho \, C_d \, \ell_d (2 \, s_1 \, \ell^3 \, r \, V + s_2 \, \ell^2 \, v_r^2) \qquad \text{(II-44(c))}$$

$$\lambda = \frac{\ell + X_s}{\ell} = \begin{array}{l}\text{The ratio of C.G. location of} \\ \text{sidewall bow to the craft} \\ \text{length}\end{array} \qquad \text{(II-44(d))}$$

$$s_1 = \frac{1 - 3\lambda(1 - \lambda)}{3} \qquad \text{(II-44(e))}$$

$$s_2 = \frac{2\lambda - 1}{2} \qquad \text{(II-44(f))}$$

$$X_{pw} = - 1/2 \, \rho \, C_f \, A_{w_p} \, u^2 \qquad \text{(II-44(g))}$$

$$= \text{port wetted area surge resistive force}$$

$$X_{sw} = - 1/2 \, \rho \, C_f \, A_{w_s} \, u^2 \qquad \text{(II-44(h))}$$

$$= \begin{array}{l}\text{starbord wetted area surge resistive} \\ \text{force}\end{array}$$

$$A_w = [2(\ell_d \pm b_o \phi) + b_s]\ell \qquad \text{(II-45)}$$

$$b_s = \frac{b_f + b_d}{2}$$

$$= \text{Average sidewall flat surface width at the keel.}$$

In equation (II-45) ± term related to the starboard or port wetted surface calculations.

2. Rudder and Propulsion Yaw Moments

The yaw moments due to the rudder and propulsion system are determined from equation (II-11(d)) and (II-13(b)) respectively.

The seals, air plenum and aerodynamic yaw moments are neglected. Actually the aerodynamic yaw moment should be taken into account. Since during the turn maneuver, the yaw drift angle is produced, thus a positive aerodynamic yaw moment contribution to the yaw motion has been generated. From 6 DOF nonlinear model simulations, this contribution is determined at 5.2% of the total yaw moment.

J. TOTAL PITCH MOMENT

The summation of the all dynamic pitch moments gives the net pitch moment which can be written as

$$M = M_{sf} + M_{sa} + M_{bf} + M_{ba} + M_{pl} + M_{sw} + M_p \qquad \text{(II-46)}$$

K. TOTAL ROLL MOMENT

Before calculating net roll moment, the roll moment equation due to the cross flow drag term must be derived. Including also the added mass effect to the equation (II-40) and (II-41), the result is

$$K_d = (D_{sw} + Y_{sw_1})(b_o \cos \beta - z_o \sin \beta) \qquad (II-47)$$

Combining all roll dynamic equations, the net roll moment is calculated as

$$K = K_{sf} + K_{sa} + K_{bf} + K_{ba} + K_{sw} + K_{pr} + K_r + K_p + K_d$$

L. TOTAL SWAY FORCE

From equation (II-11(a)), (II-12), (II-42) and (II-43), the total sway force is obtained as

$$Y = Y_r + Y_{pr} + Y_{sw} + Y_c \qquad (II-48)$$

M. TOTAL YAW MOMENT

The summation of the sidewall, rudder and propulsion yaw moments gives the net turning moment about the z-axis

$$N = N_{sw} + N_r + N_{pr} \qquad (II-49)$$

N. FIVE DEGREE-OF-FREEDOM EQUATIONS OF MOTION

Considering equations of motion for XR-3 test craft, the yaw (ψ) is defined as the rotational motion of the craft coordinate system relative to the fixed frame and the positive ψ angle is measured in the clockwise direction. This sign convention is in agreement with the rudder order sign definition. Since positive rudder angle corresponds to turning to the left, producing negative yaw moment and finally at the equilibrium condition, the negative yaw moment is generated.

Assuming small values of pitch (θ) and roll angles and relating heave motion to the free surface, the relationship between the fixed and craft coordinate system can be written. Eliminating the terms related to the fixed coordinate system, the simplified 5 DOF equations of motion are obtained as follows;

$$m \, \dot{v} = Y \qquad\qquad (II\text{-}50)$$

$$m \, \dot{w} = Z \qquad\qquad (II\text{-}51)$$

$$I_{xx} \, \dot{p} - I_{xz} \, \dot{r} = K \qquad\qquad (II\text{-}52)$$

$$I_{yy} \, \dot{q} = M \qquad\qquad (II\text{-}53)$$

$$I_{zz} \, \dot{r} - I_{xz} \, \dot{p} = N \qquad\qquad (II\text{-}54)$$

The right hand sides of the equations of motion give the forces and moments acting on the craft in terms of the craft in terms of the craft coordinate system variables. In equation (II-57) $\dot{w}$ represents heave acceleration and all other variables in these equations have already been defined.

In order to develop a 5 DOF linear model, only the surge equation of motion (x-direction) is neglected. Since from 6 DOF nonlinear simulation results, very small velocity reduction is observed during the turn maneuver of the XR-3 test craft (over the speed range 20 through 30 knots).

III.   LINEARIZATION OF THE EQUATIONS

A.   TAYLOR SERIES EXPANSION AND TOTAL DIFFERENTIAL

Generally, the linearization process can be performed by means of a Taylor series expansion using the linear part of the series (omitting high order terms). The same process can be easily done applying a total differential to the net force and moment equations, since the effect of small disturbances to the system is to be determined.

The total differential of a given dependent variable A with respect to the independent variables x, y and z is given as

$$dA \;=\; \frac{\partial A}{\partial x}\,dx + \frac{\partial A}{\partial y}\,dy + \frac{\partial A}{\partial z}\,dz \qquad\qquad (III\text{-}1)$$

B.   LINEARIZATION OF THE EQUATIONS OF MOTION AND AIR FLOW DYNAMICS

The total differentials of the equations of motion and air flow dynamics have been derived as

$$d\dot{w} \;=\; dZ/m \qquad\qquad (III\text{-}2)$$

$$d\dot{q} \;=\; dM/I_{yy} \qquad\qquad (III\text{-}3)$$

$$d\dot{m}_b \;=\; -[\rho_a\, n\, k_p + C_n\, A_\ell\, (\frac{\rho_a}{2\overline{P}_b(0)})^{1/2}]\,d\overline{P}_b \qquad (III\text{-}4)$$

$$d\dot{v} \;=\; dY/m \qquad\qquad (III\text{-}5)$$

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where $\overline{P}_b(0)$ represents the steady state value of the plenum gauge pressure according to the final equilibrium condition.

The equations (II-52) and (II-54) both involved second order yaw and roll acceleration terms. Therefore applying the total differential and solving these two equations for $d\dot{p}$ and $d\dot{r}$ we have

$$d\dot{r} = dK/I + dN/I_r \qquad \text{(III-6)}$$

$$d\dot{p} = dK/I_k + dN/I \qquad \text{(III-7)}$$

I, I_r and I_k are defined as

$$I \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{xz}} \qquad \text{(III-8(a))}$$

$$I_r \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{xx}} \qquad \text{(III-8(b))}$$

$$I_k \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{zz}} \qquad \text{(III-8(c))}$$

Equation (III-6) and equation (III-7) contain both net incremental roll (dK) and yaw (dN) moments. This is simply a cross product inertial term (I_{xz}) effect in the equations of motion.

In equation (II-59), $d\overline{P}_b$ is not a state variable, it can be considered as an output variable, therefore from equation (II-26) and (II-27), $d\overline{P}_b$ must be

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$$dP_b = \frac{\partial \overline{P}_b}{\partial z} \, dz + \frac{\partial \overline{P}_b}{\partial m_b} \, dm_b$$

C. FIVE DEGREE-OF-FREEDOM LINEAR MODEL SENSITIVITY COEFFICIENTS

The sensitivity coefficients related to the right hand side of the equations of motion are defined as the partial derivatives of the net forces and moments divided by craft mass or inertial terms.

In [2], Barnes has developed a 2 DOF (heave and pitch) linear XR-3 model. Therefore most of the neave and pitch sensitivity coefficients are directly used in order to develop a 5 DOF linear model. However some modification is made for plenum sensitivity coefficients and pitch mode. Also some of the steady state operating point values have been reinvestigated using the 6 DOF nonlinear model.

In all the linearized equations, the final steady state values of the variables have been used.

1. Pitch and Heave Sensitivity Coefficients

In [2] equation (III-40), the sensitivity coefficient due to z has been redefined as

$$DHPZ = -A_b(0) \frac{\partial \overline{P}_b}{\partial z} + \overline{P}_b(0) \frac{b_w \, \ell_9}{h}$$

This is claculated from (II-22) where the second term does not appear in [2].

The modified form of the plenum pitch sensitivity coefficient due to state variable z is to be

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$$DPPBZ = -Z_p(0) \frac{\ell_9}{2h} - X_{cp}(0) \bar{P}_b(0) \frac{b_w \ell_9}{h}$$

The derivation of these modified equations is based upon the total differential of the plenum lift force, it is

$$dZ_p = \frac{\partial Z_p}{\partial \bar{P}_b} d\bar{P}_b + \frac{\partial Z_p}{\partial A_b} dA_b$$

From equations (II-9), (II-26) and (II-27), the total differentials dV_b and $d\bar{P}_b$ have been calculated as

$$dV_b = -(A_b(0) - \ell_d(0) \frac{b_w \ell_9}{h}) \, dz \qquad \text{(III-9)}$$

$$d\bar{P}_b = \gamma \, P_b(0) [\frac{dM_b}{M_b(0)} + \frac{1}{V_b(0)} (A_b(0) - \ell_d(0) \frac{b_w \ell_9}{h})] dz . \qquad \text{(III-10)}$$

$d\bar{P}_b$ and dV_b equations are also different from the equations derived in [2].

The bow and aft seal pitch moments sensitivity coefficients (DPSFTH and DPSATH) due to θ and plenum air mass equation (AMB) are rederived and their modified forms are used for the pitch mode in the 5 DOF linear model computer program.

Considering the 5 DOF linear model state space matrix representation, the a_{ij}'s represent "A" matrix elements. Therefore the a_{ij} values relating to the sensitivity coefficients for heave motion are determined as

$$a_{21} = DZZ$$

$$a_{23} = DZTH$$

$$a_{24} = DZDP$$

$$a_{25} = DZMB$$

where DZZ, DZTH, etc., have been derived in [2]. However
their modified forms can be found in the 5 DOF linear computer
program.

For pitch motion, a_{ij} coefficients are

$$a_{41} = DTHZ$$

$$a_{43} = DTHTH$$

$$a_{44} = DTHDTH$$

$$a_{45} = DTHMB$$

2. Plenum Air Flow Sensitivity Coefficients

These coefficients are calculated directly from [2].
The a_{ij}'s related to plenum air sensitivity coefficients are

$$a_{51} = DMBZ$$

$$a_{55} = DMBMB$$

3. Sway Sensitivity Coefficients

Before deriving the sensitivity coefficients for sway motion, some partial derivatives related to the rudder and sidewall hydrodynamics must be calculated. From equation (II-11(b)) Y_r is already known, this follows the partial derivatives of Y_r with respect to the state variables

$$R_p = \frac{\partial Y_r}{\partial p} = C_t (C_e/u) \, z_s \qquad \text{(III-11)}$$

$$R_v = \frac{\partial Y_r}{\partial v} = - C_t (C_e/u) \qquad \text{(III-12)}$$

$$R_r = \frac{\partial Y_r}{\partial r} = - C_t (C_e/u) \, X_r \qquad \text{(III-13)}$$

From equation (II-39), the sidewall cross flow drag terms D_{sw} partials are derived in the following equations.

Let us define first some coefficients

$$d_1 \triangleq \frac{1}{2} \rho \, C_d \, \ell$$

$$d_r \triangleq \ell_d(0) + sign(V_r) \, b_o \, \phi(0)$$

The partials are

$$D_z = \frac{\partial D_{sw}}{\partial z} = - d_1 \, sign(V_r) \, V_r^{2}(0) \qquad \text{(III-14)}$$

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$$D_\phi = -d_1 V_r^2(0) b_o \qquad \text{(III-15)}$$

$$D_p = 2 d_1 d_r \, \text{sign}(V_r) \, V_r(0) (Z_s - \ell_d(0)/2) \qquad \text{(III-16)}$$

$$D_v = -2 d_1 d_r V_r(0) \qquad \text{(III-17)}$$

$$D_r = -2 d_1 d_r \, \text{sign}(V_r) \, V_r(0) X_s \qquad \text{(III-18)}$$

d_2 and d_3 are defined as

$$d_2 \triangleq 2 A_{33} b_o^2 u \qquad \text{(III-19)}$$

$$d_3 \triangleq A_{22} u \qquad \text{(III-20)}$$

where u is the craft speed assumed to be constant.

For sway mode, the state matrix elements are

$$a_{96} = \frac{1}{m}\left(\frac{\partial Y}{\partial \phi}\right) = \frac{1}{m}(D_\phi \sin \beta) \qquad \text{(III-21)}$$

where D_ϕ is given from equation (III-15).

$$a_{97} = \frac{1}{m}\left(\frac{\partial Y}{\partial p}\right)$$

$$= \frac{1}{m}[R_p + (R_p + d_3 Z_s)\sin \beta + d_3 Z_s] \qquad \text{(III-22)}$$

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$$a_{99} = \frac{1}{m}(\frac{\partial Y}{\partial v})$$

$$= \frac{1}{m}[R_v + (D_v - d_3)\sin \beta - d_3] \qquad (III\text{-}23)$$

$$a_{911} = \frac{1}{m}(\frac{\partial Y}{\partial r})$$

$$= \frac{1}{m}[R_r + (D_r - d_3 x_s)\sin \beta - d_3 X_s - mu]$$

$$(III\text{-}24)$$

4. Roll and Yaw Sensitivity Coefficients

Recalling equations (III-6) and (III-7), the net roll and yaw moments appear in both equations of motion. In this case, to determine sensitivity coefficients is not easy, since the yaw and roll partials are involved in the dynamic equation with different inertial terms and coefficients.

In order to simplify the problem, the roll and yaw partial derivatives are calculated individually, then combining these coefficients and dividing by corresponding inertial terms give the system sensitivity coefficients for the roll and yaw modes.

a. Roll Mode

The net roll partial derivatives are defined by k_{ij} variables.

The partial derivative with respect to z is

$$k_{71} = \frac{\partial K}{\partial z} = \frac{\partial}{\partial z}(K_{sf} + K_{sa} + K_{bf} + K_{ba}) \qquad (III\text{-}25)$$

In equation (III-26) all roll components have already been derived in the preceding sections.

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From equations (II-30) and (II-31), the seal partials are

$$\frac{\partial K_{sf}}{\partial z} = -(\frac{b_o}{2.3})^3 \rho g (1/\sin 31°) \phi(0)$$

$$\frac{\partial K_{sa}}{\partial z} = -(\frac{b_o}{2.3})^3 \rho g (1/\sin 32°) \phi(0)$$

For buoyancy partials, let us define the following coefficients;

$$b_1 \triangleq 2 \rho g \ell_1 \qquad\qquad (III-26)$$

$$b_2 \triangleq 2 \rho g \ell_2 \qquad\qquad (III-27)$$

$$b_3 \triangleq (\frac{b_f + b_w}{2}) + \frac{\ell_f}{2 \tan \beta_1} \qquad\qquad (III-28)$$

$$b_4 \triangleq \frac{\ell_f}{\tan \beta_1} + b_f \qquad\qquad (III-29)$$

$$b_6 \triangleq \frac{\ell a}{\tan \beta_2} + b_a \qquad\qquad (III-30)$$

From equations (II-35) and (II-36), the buoyancy partials are

$$\frac{\partial K_{bf}}{\partial z} = -\frac{b_1 b_3}{\tan \beta_1}(b_5 + b_3) \phi(0)$$

$$\frac{\partial K_{ba}}{\partial z} = -\frac{b_2 b_4}{\tan \beta_2}(b_6 + b_4) \phi(0)$$

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Equation (II-26) follows;

$$\frac{\partial K_p}{\partial z} = -[A_b(0) \ \overline{P}_b(0) + (Z_s - \ell_d(0) \ \frac{\partial \overline{P}_b}{\partial z}] \ \phi(0)$$

Similarly for sidewall cross flow drag partial is

$$\frac{\partial K_d}{\partial z} = D_z(b_o \ \cos \ \beta - Z_o \ \sin \ \beta)$$

The roll partial derivatives with respect to θ are

$$k_{73} = \frac{\partial K}{\partial \theta}$$

$$= \frac{\partial}{\partial \theta}(K_{sf} + K_{sa} + K_{bf} + K_{ba}) \qquad \text{(III-31)}$$

where

$$\frac{\partial K_{sf}}{\partial \theta} = (\frac{b_w}{2.3})^3 \ \rho \ g(\ell_3/\sin \ 31°) \ \phi(0)$$

$$\frac{\partial K_{sa}}{\partial \theta} = - (\frac{b_w}{2.3})^3 \ \rho \ g(\ell_4/\sin \ 32°)$$

$$\frac{\partial K_{bf}}{\partial \theta} = \frac{b_1 \ b_2}{\tan \ \beta_1}(b_5 + b_3 \ \ell_5) \ \phi(0)$$

$$\frac{\partial K_{ba}}{\partial \theta} = - \frac{b_2 \ b_4}{\tan \ \beta_2}(b_6 + b_4 \ \ell_3) \ \phi(0)$$

The roll partial derivative with respect to M_b is

$$k_{75} = \frac{\partial K_p}{\partial M_b}$$

$$= A_b(0)(Z_s - \ell_d(0)) \frac{\partial \overline{P}_b}{\partial M_b} \phi(0) \qquad \text{(III-32)}$$

The roll partials with respect to ϕ are

$$k_{76} = \frac{\partial K}{\partial \phi}$$

$$= \frac{\partial}{\partial \phi}(K_{sf} + K_{sa} + K_{bf} + K_{ba} + K_p + K_d) \qquad \text{(III-33)}$$

where

$$\frac{\partial K_{sf}}{\partial \phi} = -(b_w/2.3)^3 \rho g X_f$$

$$\frac{\partial K_{sa}}{\partial \phi} = -(b_w/2.3)^3 \rho g X_a$$

$$\frac{\partial K_{bf}}{\partial \phi} = -b_1 b_3^2 b_5$$

$$\frac{\partial K_{ba}}{\partial \phi} = -b_2 b_4^2 b_6$$

$$\frac{\partial K_p}{\partial \phi} = \overline{P}_b(0)(Z_s - \ell_d(0)) \ell b_w$$

$$\frac{\partial K_d}{\partial \phi} = D_\phi (b_o \cos \beta - Z_o \sin \beta)$$

The roll partials with respect to p are

$$k_{77} = \frac{\partial K}{\partial p}$$

$$= \frac{\partial}{\partial p}(K_{sw} + K_d + K_r) \qquad (III-34)$$

where

$$\frac{\partial K_{sw}}{\partial p} = -d_2 - Z_s^2 A_{22} u - 32/\pi \, b_o^2 \, B_c$$

$$\frac{\partial K_d}{\partial p} = (D_p + \frac{\partial Y_{sw_1}}{\partial p}) (b_o \cos \beta - Z_o \sin \beta)$$

The roll partials with respect to V are

$$k_{79} = \frac{\partial K}{\partial V}$$

$$= \frac{\partial}{\partial V}(K_{sw} + K_d + K_r) \qquad (III-35)$$

where

$$\frac{\partial K_d}{\partial V} = (D_v - d_3)(b_o \cos \beta - Z_o \sin \beta) + d_3 \, X_s \, Z_s$$

$$\frac{\partial K_{sw}}{\partial V} = d_3 \, Z_s$$

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$$\frac{\partial K_r}{\partial V} = C_t(C_e/u) Z_r$$

The roll partials with respect to yaw rate are

$$k_{711} = \frac{\partial K}{\partial r}$$

$$= \frac{\partial}{\partial r}(K_{sw} + K_d + K_r) \qquad \text{(III-36)}$$

where

$$\frac{\partial K_{sw}}{\partial r} = d_3 X_s Z_s$$

$$\frac{\partial K_{sw}}{\partial r} = (D_r - d_3 X_s)(b_o \cos \beta - Z_o \sin \beta)$$

$$\frac{\partial K_r}{\partial r} = C_t(C_e/u) X_r Z_r$$

b. Yaw Mode

The following coefficients are defined for yaw rotational motion;

$$n_1 \triangleq 2 A_{22} \ell(1 - \lambda) \qquad \text{(III-37)}$$

$$n_2 \triangleq -\pi/5 \rho u \ell \qquad \text{(III-38)}$$

$$n_3 \triangleq -\text{sign}(V_r) \rho C_d \ell_d(0) \qquad \text{(III-39)}$$

$$C_1 \triangleq 2 S_1 \ell^3 \qquad\qquad (III\text{-}40)$$

$$C_2 \triangleq S_2 \ell^2 \qquad\qquad (III\text{-}41)$$

$$X_w \triangleq -1/2 \rho C_f u^2 \ell \qquad\qquad (III\text{-}42)$$

The net yaw partial derivatives are defined by n_{ij} variables.

The yaw partials with respect to ϕ are

$$
\begin{aligned}
n_{116} &= \frac{\partial N_{sw}}{\partial \phi} \\
&= \frac{\partial N_1}{\partial \phi} + \frac{\partial}{\partial \phi}(X_{pw} - X_{sw}) b_o \qquad (III\text{-}43)
\end{aligned}
$$

where

$$\frac{\partial N_1}{\partial \phi} = 4 n_2 V(0) b_o^2 \phi(0)$$

$$\frac{\partial}{\partial \phi}(X_{pw} - X_{sw}) = -4 X_w$$

The yaw partials with respect to p are

$$n_{117} = \frac{\partial N}{\partial p} = \frac{\partial}{\partial p}(N_{sw} + N_r) \qquad (III\text{-}44)$$

The N_{sw} and N_r partial derivatives can be calculated from equations (II-44(a)) and (II-11(d)).

The yaw moments partial derivatives with respect to V and r are derived similarly, the n_{ij} coefficients related to these modes are

$$n_{119} = \frac{\partial N}{\partial V} \qquad \text{(III-45)}$$

$$n_{1111} = \frac{\partial N}{\partial r} \qquad \text{(III-46)}$$

c. Roll Sensitivity Coefficients

The roll sensitivity coefficients corresponding to state matrix elements a_{ij}'s are determined from equation (III-7). They are

$$a_{71} = k_{71}/I_k$$

$$a_{73} = k_{73}/I_k$$

$$a_{75} = k_{76}/I_k$$

$$a_{76} = k_{76}/I_k + n_{116}/I$$

$$a_{77} = k_{79}/I_k + n_{119}/I$$

$$a_{711} = k_{711}/I_k + n_{1111}/I$$

where inertial terms I and I_k are found from equations (III-8(a)) and (III-8(c)).

d. Yaw Sensitivity Coefficients

For yaw motion, the sensitivity coefficients a_{ij}'s have been determined from equation (III-6).

These coefficients are listed below;

$$a_{111} = k_{71}/I$$

$$a_{113} = k_{73}/I$$

$$a_{115} = k_{75}/I$$

$$a_{116} = k_{76}/I + n_{116}/I_r$$

$$a_{117} = k_{79}/I + n_{119}/I_r$$

$$a_{1111} = k_{711}/I + n_{1111}/I_r$$

where the inertial term I_r is calculated from equation (III-8(b)).

D. STATE SPACE REPRESENTATION AND OUTPUT EQUATION

The state vector of the linear 5 DOF model is shown as

$$X = [dZ\ dW\ d\theta\ dq\ dM_b\ d\phi\ dp\ dy\ dV\ d\psi\ dr]^T \tag{III-47}$$

Then, the system state equation must be

$$\dot{X} = Ax + Bu \tag{III-48}$$

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And the output equation is

$$y = C X \qquad (III-49)$$

"A" matrix elements have already been determined. However for "B" matrix elements, the step input to the system can be considered as a weight removal disturbance and for the roll and yaw modes, a rudder order disturbance.

For weight removal forcing function, the input is to be

$$b_{21} = \frac{W_f - W_i}{m} \qquad (III-50)$$

where

$$W_f = \text{final craft weight}$$

$$W_i = \text{initial craft weight}$$

$$m = \text{craft mass corresponding to the final weight } W_f.$$

When the rudder order is used, sway, roll and yaw forcing functions are generated as follows;

sway $\qquad b_{91} = \frac{1}{m}(2 X_t \sin \delta_r + C_t \delta_r) \qquad (III-51)$

roll $\qquad b_{71} = (2 X_t \sin \delta_r + C_t \delta_r)(- z_r/I_k + x_r/I)$

yaw $\qquad b_{111} = (2 X_t \sin \delta_r + C_t \delta_r)(x_r/I_r + z_r/I)$

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Finally, defining state variables x_1, x_2, ..., etc., the state equations of the 5 DOF linear model are given as follows;

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = a_{21}x_1 + a_{23}x_3 + a_{24}x_4 + a_{25}x_5$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = a_{41}x_1 + a_{43}x_3 + a_{44}x_4 + a_{45}x_5$$

$$\dot{x}_5 = a_{51}x_1 + a_{55}x_5$$

$$\dot{x}_6 = x_7$$

$$\dot{x}_7 = a_{71}x_1 + a_{73}x_3 + a_{75}x_5 + a_{76}x_6 + a_{77}x_7$$
$$+ a_{79}x_9 + a_{711}x_{11}$$

$$\dot{x}_8 = x_9$$

$$\dot{x}_9 = a_{96}x_6 + a_{97}x_7 + a_{99}x_9 + a_{911}x_{11}$$

$$\dot{x}_{10} = x_{11}$$

$$\dot{x}_{11} = a_{111}x_1 + a_{113}x_3 + a_{115}x_5 + a_{116}x_6$$

$$+ a_{117}x_7 + a_{119}x_9 + a_{1111}x_{11}$$

All coefficients of the state equations are defined in the preceding sections.

Considering outputs of the linear model, only incremental changes of the variables can be observed.

IV. LINEAR FIVE DEGREE-OF-FREEDOM COMPUTER PROGRAM DESCRIPTIONS

The Digital Simulation Language (DSL/360) is used for the linear 5 DOF XR-3 computer program. Eleven first order integrator blocks are needed for five degree of freedom simulations and for all linear runs, fourth order Runge-Kutta with fixed interval integration method is selected.

In addition to the craft dimensional values, initial and final steady state operating points are entered into the program for linearization purposes and plot outputs.

The input parameters of this program are

V = Craft speed (ft/sec)

WF = Final craft weight (lb)

W = Initial craft weight (lb)

RUDANG = Rudder input (positive for port turn)

DR = Average deadrise angle

PBBAR = Final steady state value of plenum pressure (lb/ft^2)

ALD = Final steady state craft draft (inches)

PHI = Final steady state roll angle

FYP = The propulsion system thrust corresponding to the craft speed (for each of propellers)

VL = Steady state lateral speed (ft/sec)

R = Steady state yaw rate (rad/sec).

The steady state values of the variables are determined
from 6 DOF nonlinear model simulations.

V. SIX DEGREE-OF-FREEDOM NONLINEAR MODEL SIMULATIONS

In this chapter 6 DOF nonlinear model simulations are discussed.

At first, some of the runs are made in order to determine craft initial steady state operating point corresponding to craft speed and thrust inputs. Since 6 DOF model weight transient response can be analyzed by means of entering proper craft initial values into the program, this is simply an initial condition response of the nonlinear dynamic system.

A. WEIGHT REMOVAL TRANSIENT

For 30 and 20 knot craft speeds, the steady state values of some variables are listed in Table I.

Table I

Steady State Values of the Weight Removal Response

Speed (knt)	Pitch (degree)	$\overline{P}_b$ (lb/ft^2)	Draft (inch)	Thrust (lb)	Weight (lb)
30	0.95	24.8	8.6	355.6	6722
30	0.26	24.8	5.6	287.8	6050
20	0.45	24.8	6.06	186.2	6050

For 30 knot craft speed, two different steady state pitch angles are observed corresponding to the different weights. In [2] for pitch transient response, 0.65° steady state pitch angle value has been used for both linear and nonlinear

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simulations. On the other hand as seen in Table I, 0.26°
and 0.95° steady state pitch values are obtained. This dis-
agreement may be explained by noting that different dimensional
values were used or more probably a different modified 6
DOF computer program deck was used.

For 6050 lb craft weight, the steady state pitch angle
0.26° is in agreement with the value determined by Menzel in
figure 6 in [6].

During the weight removal response, simulations of 6 DOF,
two different stern seal base leakage areas are used. In [1]
a smaller leakage area is assumed for the linear heave only
model as $A_\ell = 0.384$. However $A_\ell = 3.84$ also has been simulated
and it is understood that the smaller leakage area is more
reasonable considering other steady state variables in the
air flow dynamic equations (II-23) and (II-24). Since at
the steady state condition $Q_{in} = Q_{out}$ must be satisfied, that
permits only smaller A_ℓ for a given Q_o and $\bar{P}_b$ steady state
values. Therefore $A_\ell = 0.384$ is preferred and used for
nonlinear simulations.

B. TURNING MANEUVER

When the 3 DOF pitch, heave and roll linear model was
developed, the 6 DOF nonlinear model simulations were used
in order to determine all steady state roll moments during
the turn maneuver. In addition to the roll moments, yaw
and sway outputs were also investigated and the results are
tabulated in Tables II, III and IV.

Table II

Steady State Roll Moments

(rudder = 5°, 30 knot speed)

Roll Moments	Positive	Negative
Stern seal FKSS	-	-2.2
Bow seal FKBS	-	-280.
Sidewall FKSW	-	-41.5
Rudder FKRUD	131.	-
Propulsion FKP	0.057	-
Aerodynamic FKAED	-	-22.7
Plenum ABPB*PHI*(-Z)	215.3	-

Table III

Steady State Yaw Moments

(rudder = 5°, 30 knot speed)

Yaw Moments	Positive	Negative
Stern seal FNBS	3.22	-
Bow seal FNSS	0.	0.
Sidewall FNSW	-	-482.2
Rudder FNRUD	532.65	-
Propulsion FNP	2.78	-
Aerodynamic FNAED	-	- 56.41

Table IV

Steady State Sway Forces

(rudder = 5°, 30 knot speed)

Sway Forces	Positive	Negative
Sidewall FYSW	-	-351.8
Rudder FYRUD	-	- 47.6
Aerodynamic FYAED	-	- 19.07
Centrifugal -R*U*AM	419.24	-

From Table II, it is understood that for a given (+) rudder input, the sign convention of the craft dynamics was in agreement with turning to the left. However, a negative sway displacement plot is observed for this maneuver. As a result, in the R.H.S. subroutine of the 6 DOF program, the sign correction should be done for y-displacement.

The steady state sway forces acting on the XR-3 test craft in a turn to the left are shown in figure 6. As seen in this figure and from Table IV, the rudder sway force is in the steady state condition. For a left turn, initially the rudder sway force is generated in the reverse direction and finally a negative steady state rudder sway force is produced. Further investigation is done in the RUDDER subroutine dynamic equations of the 6 DOF computer model, but no error has been determined in these equations. Also, different craft speeds and different effective rudder angle coefficients (ENDFAC) are used but everytime the same configuration is observed.
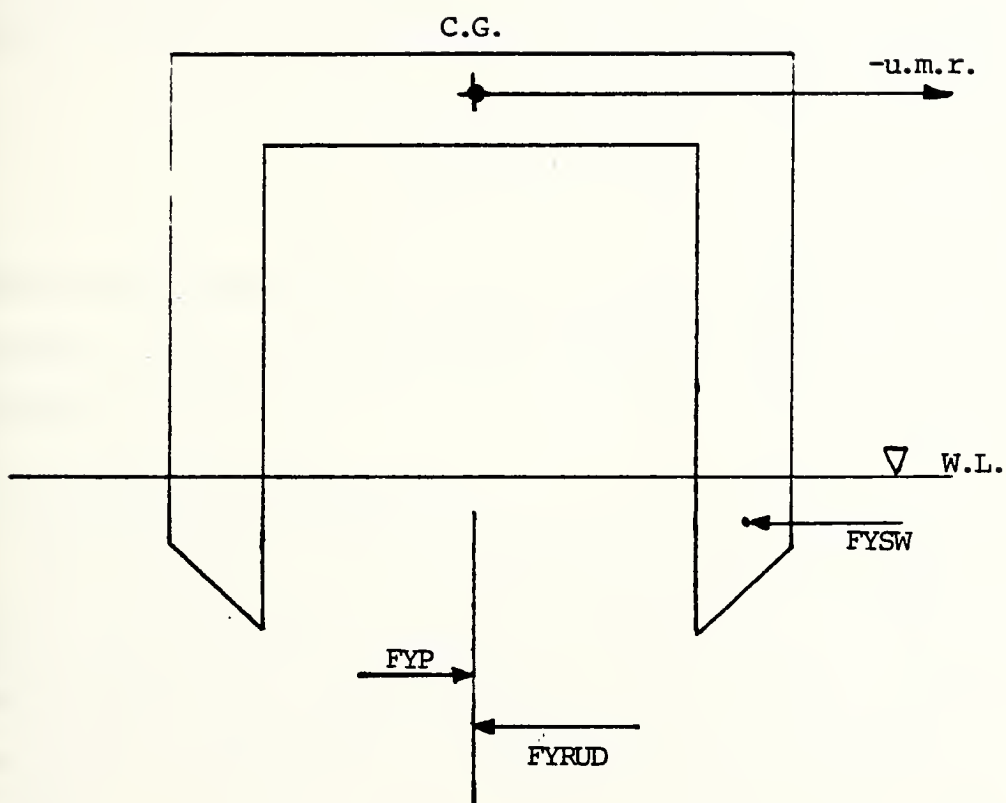
Figure 6. Steady state sway forces configuration at the left turn

In addition to rudder dynamics, the propulsion system of the XR-3 contributes to the roll, yaw and sway motions. However this contribution is not a dominant factor compared with the rudder effect.

For the XR-3 test craft propulsion system configuration, the direction of the thrust vector is also changed as well as the rudder deflection. As seen from Tables II, III and the simulations with different rudder order, it is understood that the propulsion thrust component due to the rudder order is not calculated properly, therefore the following modification is made in the PROPULSION subroutine of the 6 DOF program,

$$FYS = -STHSTS*CD+THSS*CD$$

where FYS represents the sway force due to the starboard propeller, and the others are defined in the propulsion subroutine program.

C.   DEADRISE ANGLE EFFECT

As reported in [4], the deadrise angle has a major effect on the surface effect ship's roll behavior and therefore is an important design consideration. The deadrise angle effect on the roll motion has been investigated by Reidel in [3]. In this investigation, some arbitrary coefficients (PROMO 1, 2, etc.) are used for the vertical force component of the sidewall hydrodynamics. From this investigation, the conclusion reported by Reidel was that more damping could be obtained for the pitch and roll motions by changing the deadrise angle.

The deadrise effect is reinvestigated by simulating the system with different rudder orders including zero disturbance, then the heave forces due to sidewall hydrodynamics were compared to each others. As a result, no significant sidewall heave force change was observed. For instance, for 0° and 5° rudder inputs, the sidewall heave forces (FZSW) are found to be -568.8 and -568.05 respectively. This result is not acceptable, since in a turn maneuver, the cross flow drag is generated at the outboard sidewall, so the deadrise projection of cross flow drag must be contributed to the sidewall heave force. More investigation has been made in the SIDEWALL subroutine of the 6 DOF program and it has been determined that only the force component due to added mass given by equation (II-21) is projected as a lift force. Actually the cross flow drag component must be included to this projection, since the frontal area for cross flow drag component is outboard of the submerged section of the sidewall. Therefore it is concluded that the XR-3 test craft 6 DOF program SIDEWALL subroutine does not include effectively the lift force due to deadrise. On the other hand, the lift force and horizontal drag component can have different drag coefficients, therefore the modification of the sidewall subroutine is left for future studies.

VI.   COMPARISON OF NONLINEAR AND LINEAR MODEL RESULTS

A.   C.G. ACCELERATION (see figs. 9 and 23)

A 10% weight removal disturbance is used for both models.
The linear and nonlinear model showed very rapid response
with small rise time. As seen in figure 9, the 6 DOF model
transient is relatively more damped compared with the linear
model response. The linear model showed a small overshoot
but it is also sufficiently damped. Small oscillatory behavior
is observed in both figures which is due to pitch-heave
coupling. In general the two models agree in transient response
and steady state behavior.

Both of the C.G. acceleration curves were normalized by a
factor "g", the gravitational constant.

B.   PITCH TRANSIENT (see figs. 10 and 24)

As seen in these figures, both models showed an oscillatory
transient response with the same frequency, $w \doteq 3.12$ rad/sec.
However their steady state values are different. In fact,
the pitch moment due to plenum pressure and the effective
plenum pressure center play a dominant role for pitch motion.
In [2] Barnes developed plenum modeling including effective
plenum roof area calculations and plenum pressure centroid
shift due to draft variation. Therefore the linear model
plenum modeling is different from the nonlinear modeling,
so that a greater plenum moment arm is calculated in the linear
model.

The steady state pitch angle values are 0.5° and 0.75° for nonlinear and linear models correspondingly.

C. PLENUM PRESSURE TRANSIENT (see figs. 7 and 21)

As seen in these figures, both models are exactly in agreement with each other. In each curve, the plenum pressure suddenly drops to 21.6 (lb/ft^2) then increases up to its steady state value with sufficient damping. This is expected behavior because the plenum volume increases when 10% weight is removed, obviously this disturbance causes a sudden drop in plenum pressure. As seen before, pitch-plenum pressure coupling had been observed during the exponential increasing phase of the plenum pressure. At the fifth second of simulation time, nonlinear model plenum pressure is about 24.29 while the linear model pressure is 24.25.

D. DRAFT TRANSIENT (see figs. 8 and 22)

Excellent agreement was achieved between linear and non-linear model draft responses. As expected, the draft decreases exponentially when the weight is removed from the craft. The draft is found to be 5.7 inches for the linear model, 5.85 inches for the nonlinear model at the fifth second of simulation time.

As a result, both models exhibited the same draft responses.

E. ROLL RESPONSE

As mentioned before, at first a 3 DOF linear model (pitch-heave-roll) had been developed. 3 DOF linear and 6 DOF

nonlinear models roll behavior comparison is done by means
of a step input roll moment disturbance to the linear model
and a turning command to the nonlinear model. In figure 13
6 DOF nonlinear model roll angle response is shown for a 5°
rudder order (left turn), in this simulation 1.18° outboard
steady state roll angle is generated. From the R.H.S. sub-
routine of the 6 DOF program, all the steady state roll moment
components are determined as seen in Table II and the sum of
these disturbance moments applied to the linear model roll
mode as a step input. Roll behavior is analyzed from figure
27. As expected, the linear model showed a greater overshoot
and more oscillatory response compared with the nonlinear
roll transient. Since the linear model has been disturbed
by a step roll moment corresponding to the nonlinear model
steady state roll moments. On the other hand, its steady
state roll angle is found to be 1.28°. The roll steady state
difference of two models is about 8.4%. For a 3° rudder input,
nonlinear and linear simulations are obtained in figures 11
and 25 with the steady state values 0.62° and 0.65° respec-
tively. Hence the difference is 4.8% in the steady state
values for these simulations.

Figures 12 and 14 show XR-3 yaw rate plots and corres-
ponding linear simulations are shown in figures 26 and 28.

As a result, the 3 DOF linear model and 6 DOF program
roll simulations are in agreement with each other within
10% difference.

As discussed in the previous chapter, some problems
are observed in the 6 DOF nonlinear program. Therefore
developing two more modes for the 3 DOF model, the 5 DOF
linear model has been generated. By means of this model,
roll behavior of the XR-3 in a turn, deadrise angle and
cross product inertial term effects have been investigated
for 20 knot craft speed with different rudder deflections.

The roll response can be seen in figure 29 omitting the
cross product inertial term (I_{xz} = -2800.) in the equations
of motion, applying a 10° rudder order and assuming 70 degree
average deadrise angle of the craft. For this particular
test, the craft starts inboard rolling with the oscillatory
transient then goes to 0.47° steady state roll. Using the
same input parameters and also including the cross product
term I_{xz} in the equations of motion, smaller overshoot (18%)
and a more damped roll response has been observed in figure
31. As seen in this figure, at the initial phase, secondary
overshoot has been generated. The steady state roll angle is
0.40° and the oscillation frequency w = 3.5 rad/sec., for
this simulation. On the other hand, the corresponding 6 DOF
nonlinear simulation is shown in figure 17 and also a roll
rate plot is shown in figure 18. The nonlinear simulation
in figure 17 shows a more damped transient but greater steady
state roll behavior (1.32°) compared with the corresponding
linear simulation shown in figure 31.

Figures 30 and 32 present linear simulation curves for 5 and 15 degree rudder inputs respectively. Both curves exhibit the same linear model response discussed before. Finally the linear and nonlinear model steady state responses are summarized as follows.

Rudder	6 DOF Nonlinear	5 DOF Linear	Reference
5	0.57	0.24	figures 15 and 30
10	1.32	0.40	figures 17 and 31
15	2.2	0.45	figures 19 and 32

The deadrise angle effect is investigated by using different deadrise angle values for 10 degree rudder input and 20 knot craft speed simulations. The results are tabulated in Table V.

Table V

Sidewall Deadrise Angle Effect

(rudder = 10°, 20 knot speed)

Deadrise angle (degree)	Roll angle (degree)	Lateral Speed (ft/sec)	Yaw rate (rad/sec)
45	-1.01	4.18	-0.064
50	-0.84	4.04	-0.069
55	-0.62	3.90	-0.076
60	-0.30	3.83	-0.080
65	0.02	3.73	-0.085
70	0.40	3.60	-0.100

For the linear model, the lateral velocity and yaw rate plots are shown in figures 33 and 34. Both of them showed sufficiently damped transient response. From figure 33, the lateral speed steady state value is found 3.6 (ft/sec) and as expected for turning to the left, the negative yaw rate is generated as -0.1 (rad/sec).
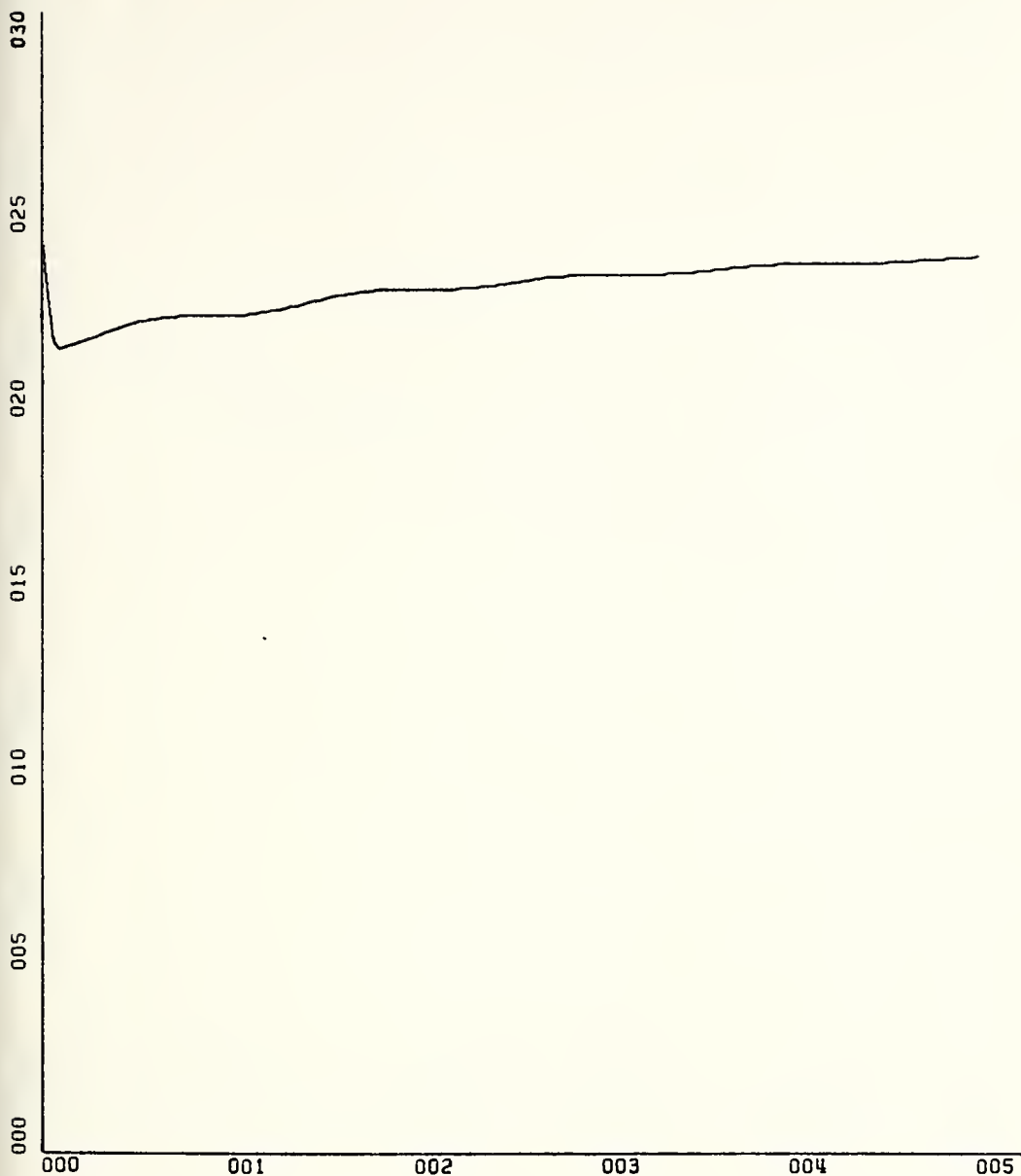
X-SCALE=1.00E+00 UNITS INCH.
Y-SCALE=5.00E+00 UNITS INCH.
XR-3 30 KNOTS SPEED
PLOT IS PLENUM PRESSURE

Figure 7.   6 DOF Plenum pressure transient
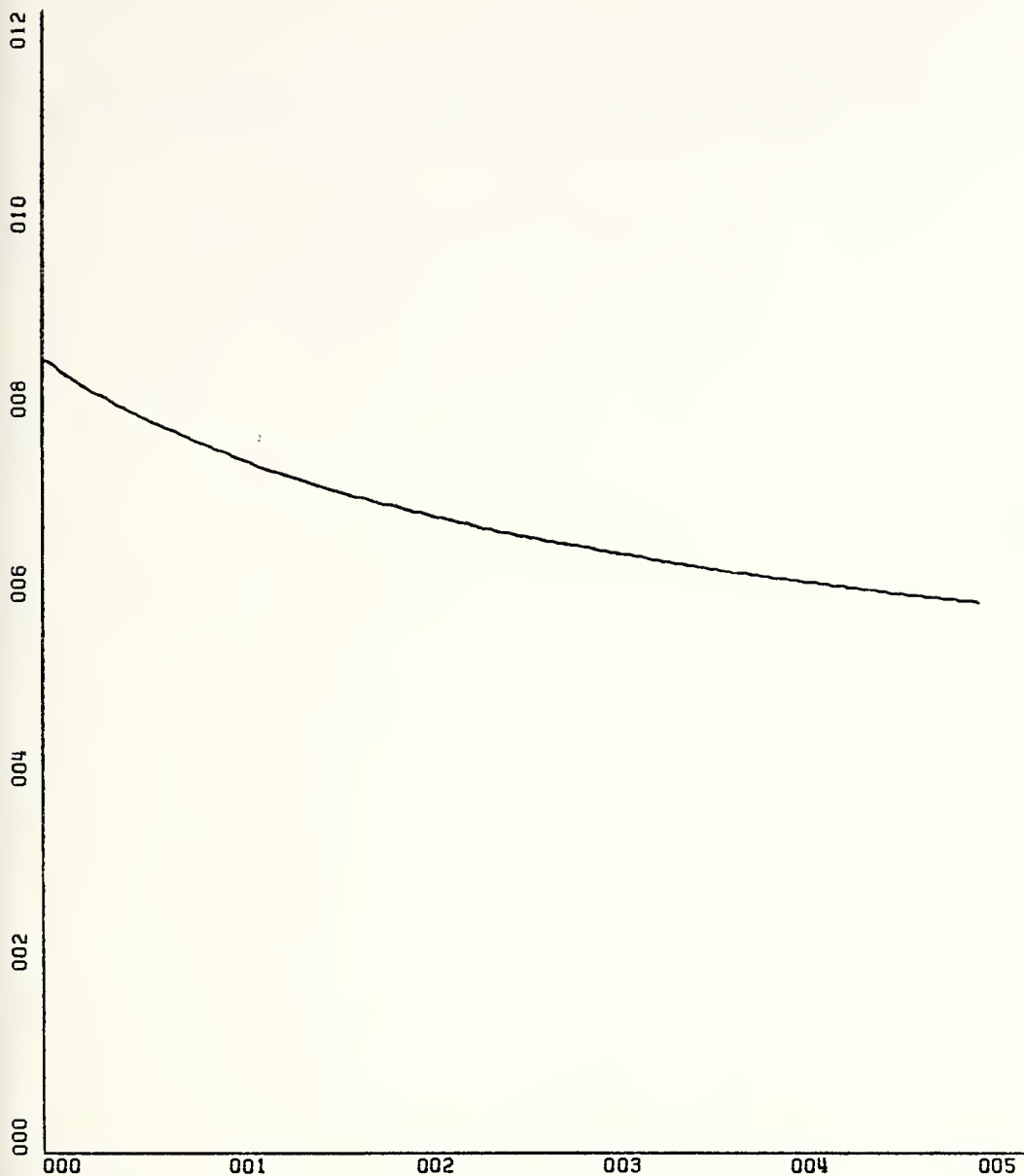
X-SCALE=1.00E+00 UNITS INCH.
Y-SCALE=2.00E+00 UNITS INCH.
XR-3 30 KNOTS SPEED
PLOT IS Z DISPLACEMENT

Figure 8.   6 DOF draft transient
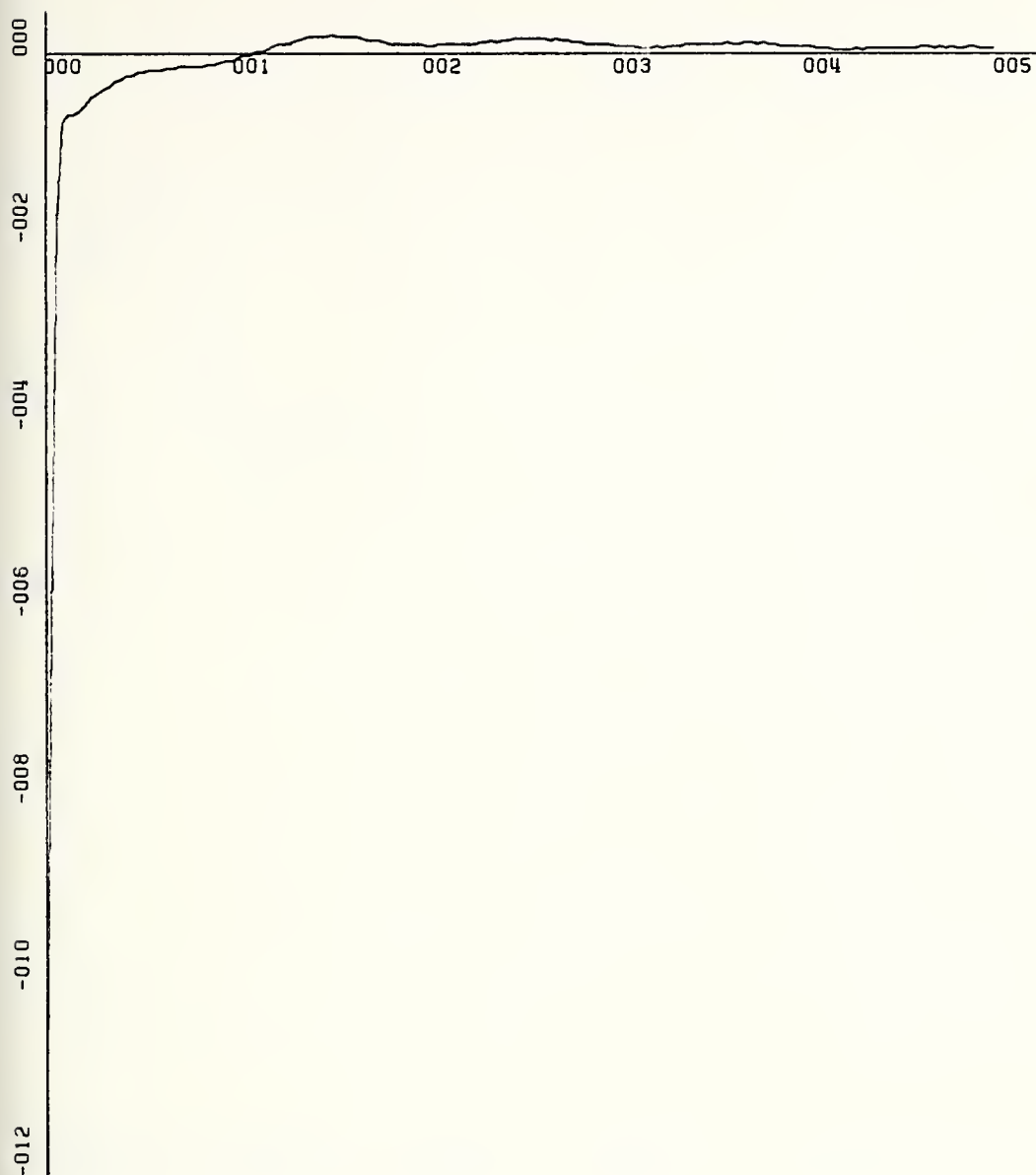
X-SCALE=1.00E+00 UNITS INCH.
Y-SCALE=2.00E-02 UNITS INCH.
XR-3 30 KNOTS SPEED
PLOT IS C.G.ACCELERATION

Figure 9.   6 DOF C.G. Acceleration
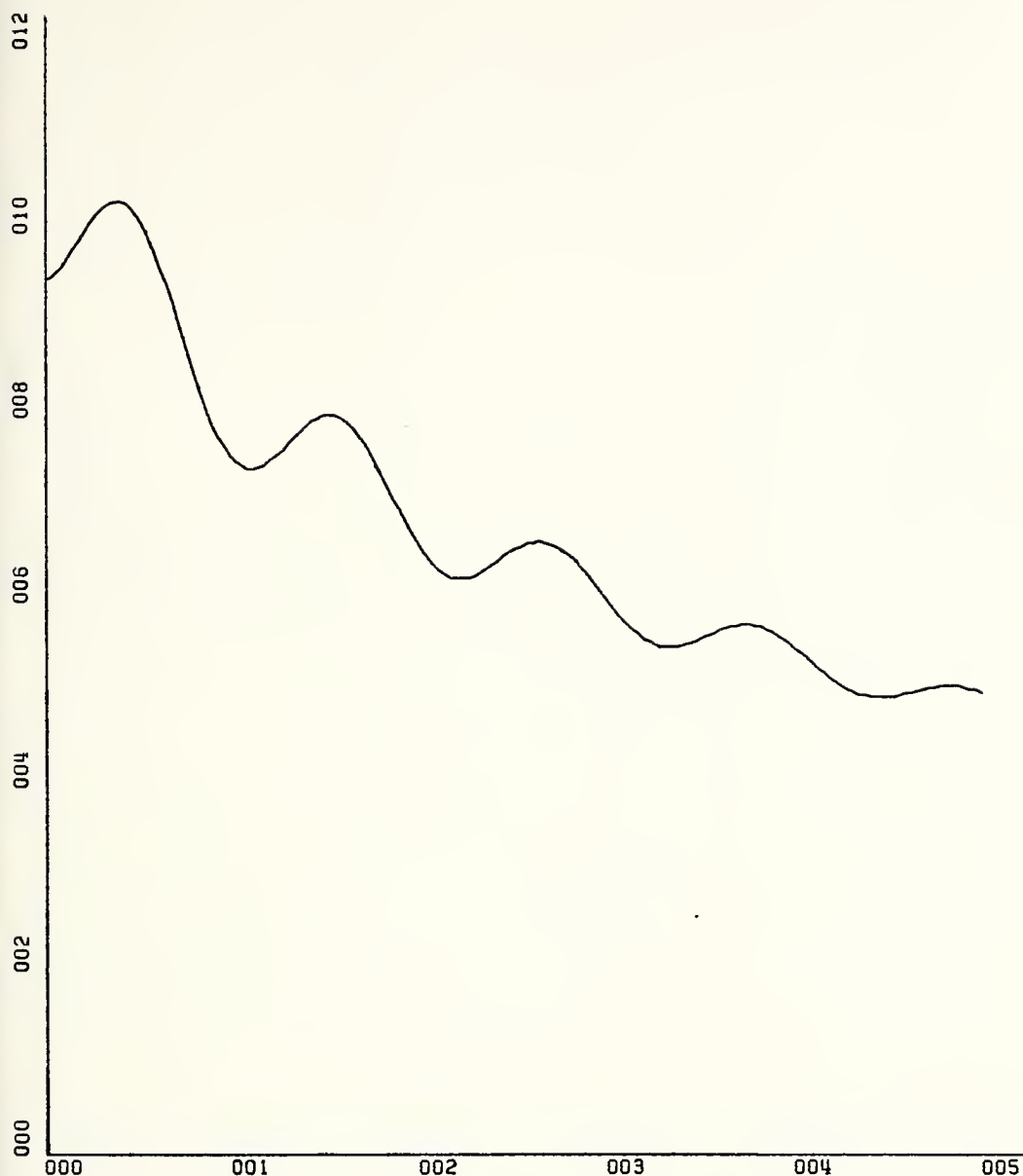
X-SCALE=1.00E+00 UNITS INCH.
Y-SCALE=2.00E-01 UNITS INCH.
XR-3 30 KNOTS SPEED
PLOT IS PITCH ANGLE

Figure 10. 6 DOF pitch angle transient
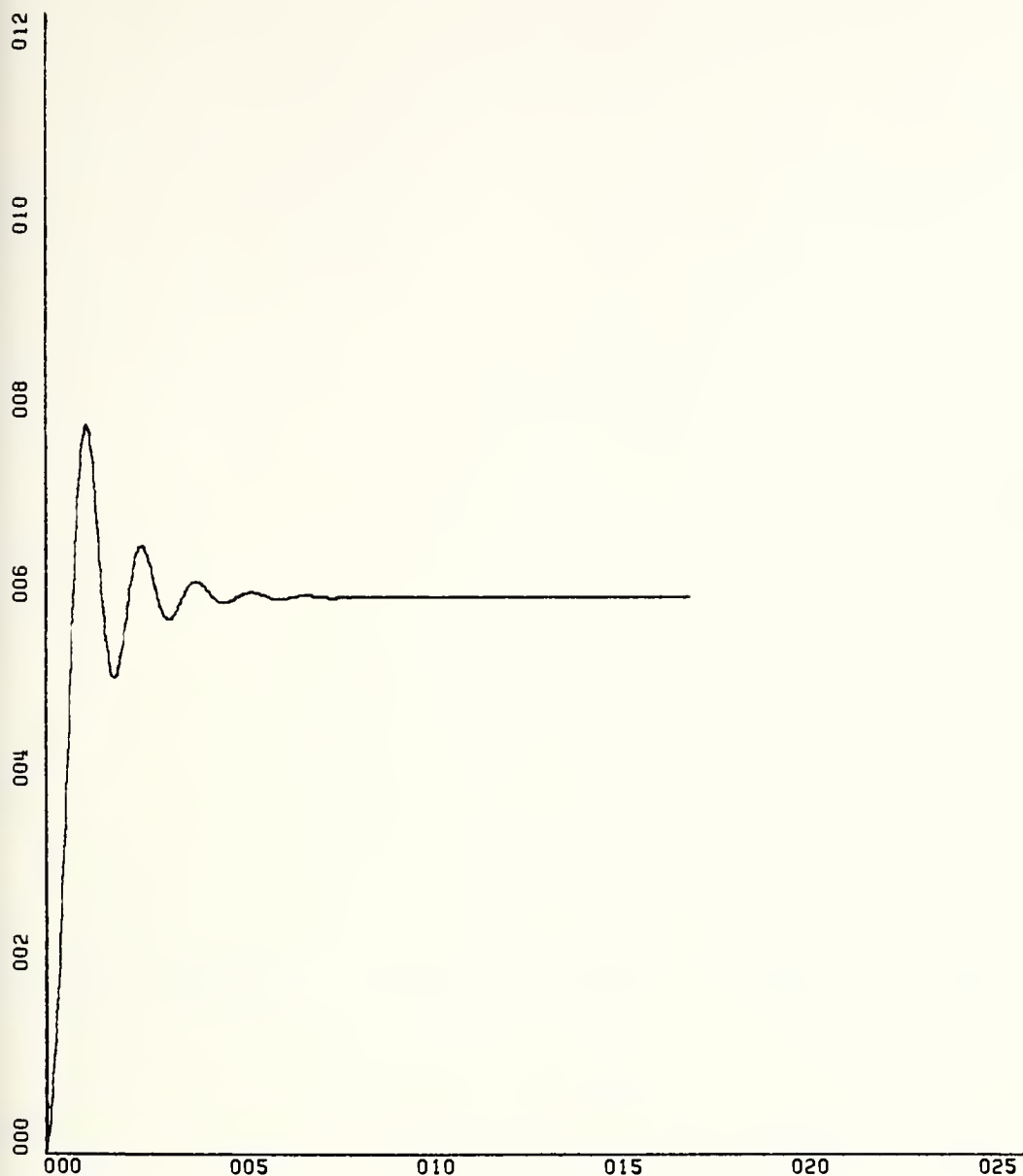
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E-01 UNITS INCH.
XR-3 30 KNOTS SPEED RD=3
PLOT IS   ROLL ANGLE

Figure 11.   6 DOF Roll angle plot, δ_r = 30°
             30 knot speed
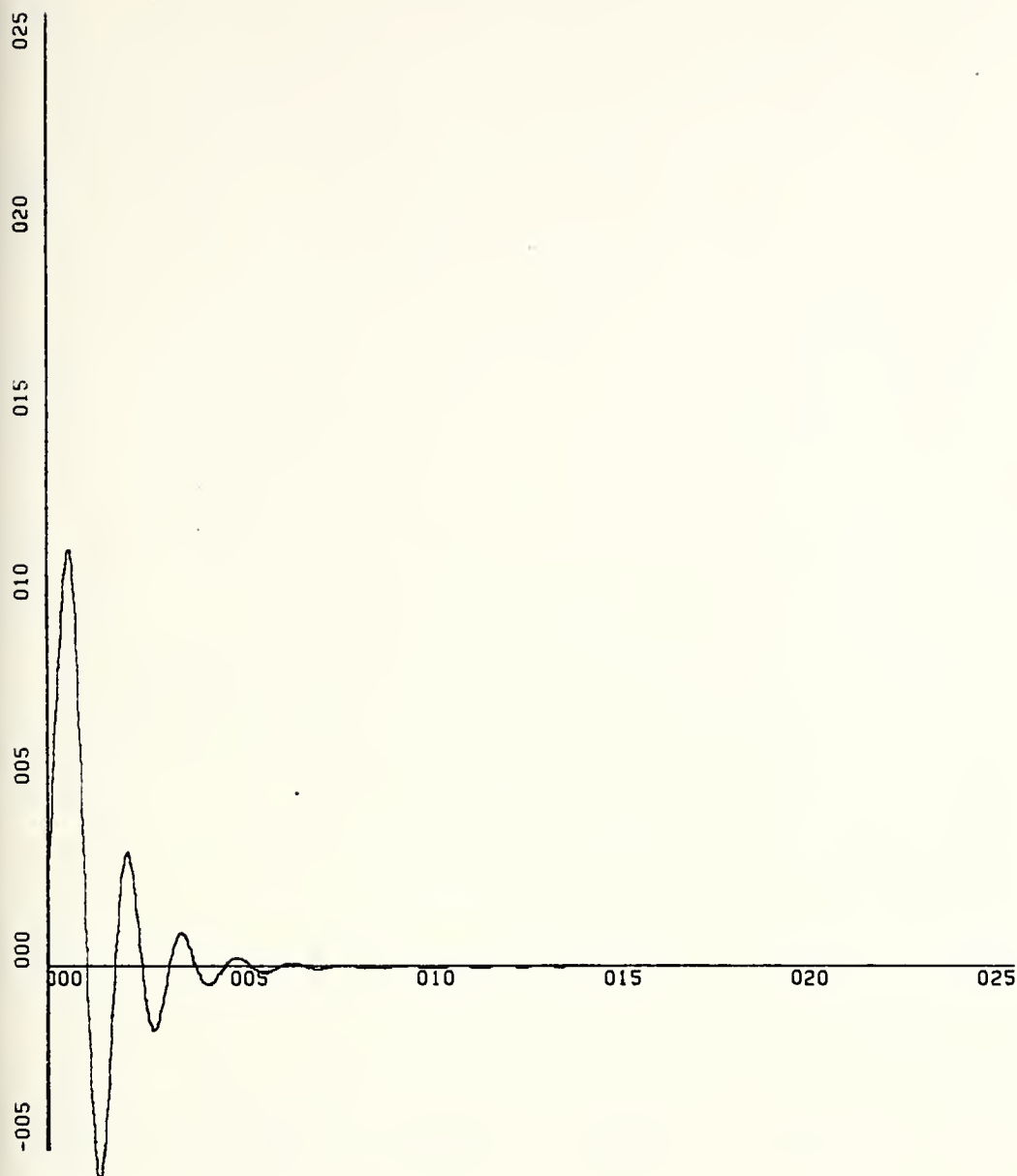
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
XR-3 30 KNOTS SPEED RD=3
PLOT IS ROLL RATE

Figure 12.   6 DOF roll rate plot, δ_r = 3°
             30 knot speed

X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
XR-3 30 KNØTS SPEED RD=5
PLØT IS   RØLL ANGLE

Figure 13.   6 DOF roll angle plot, δ_r = 5°
             30 knot speed
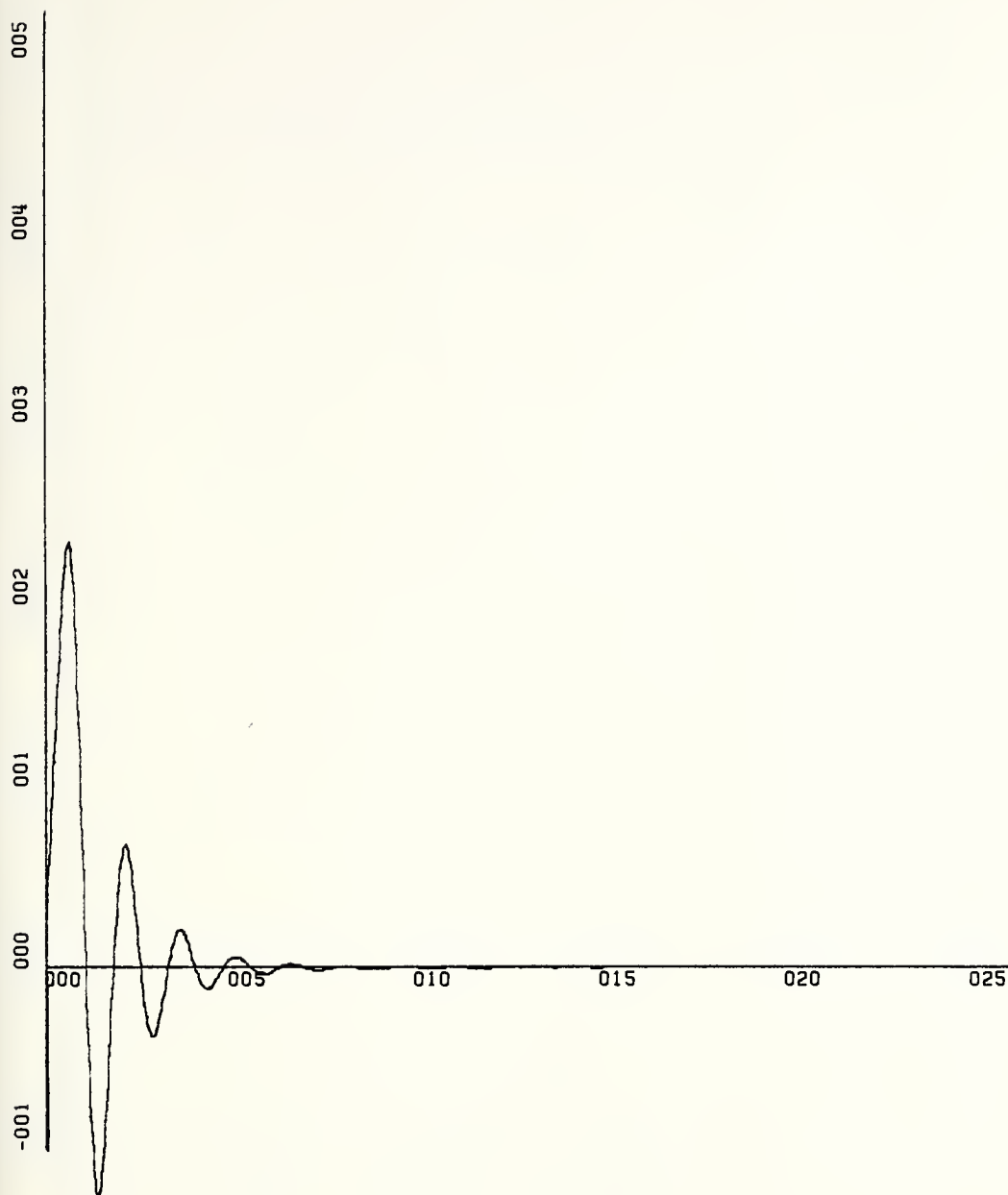
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
XR-3 30 KNOTS SPEED RD=5
PLOT IS ROLL RATE

Figure 14.   6 DOF roll rate plot, δ_r = 5°
                30 knot speed

X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
XR-3 20 KNOTS SPEED RD=5
PLOT IS   ROLL ANGLE

Figure 15.   6 DOF roll angle plot, δ_r = 5°
             20 knot speed

X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E-01 UNITS INCH.
XR-3 20 KNOTS SPEED RD=5
PLOT IS ROLL RATE

Figure 16.   6 DOF roll rate plot, $\delta_r = 5°$
20 knot speed
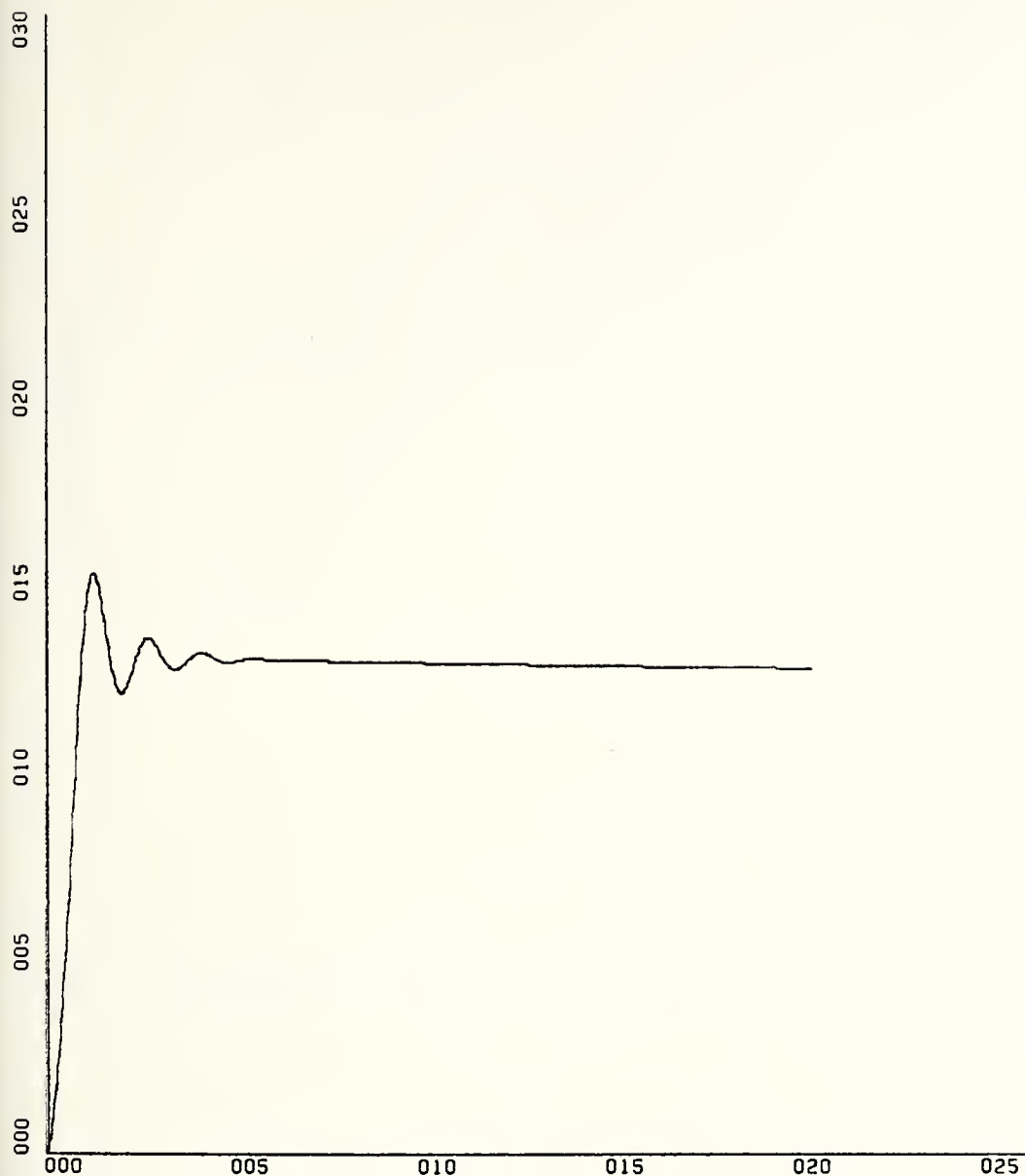
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
XR-3 20 KNOTS SPEED RD=10
PLOT IS   ROLL ANGLE

Figure 17.   6 DOF roll angle plot, δ_r = 10°
              20 knot speed

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X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
XR-3 20 KNOTS SPEED RD=10
PLOT IS ROLL RATE

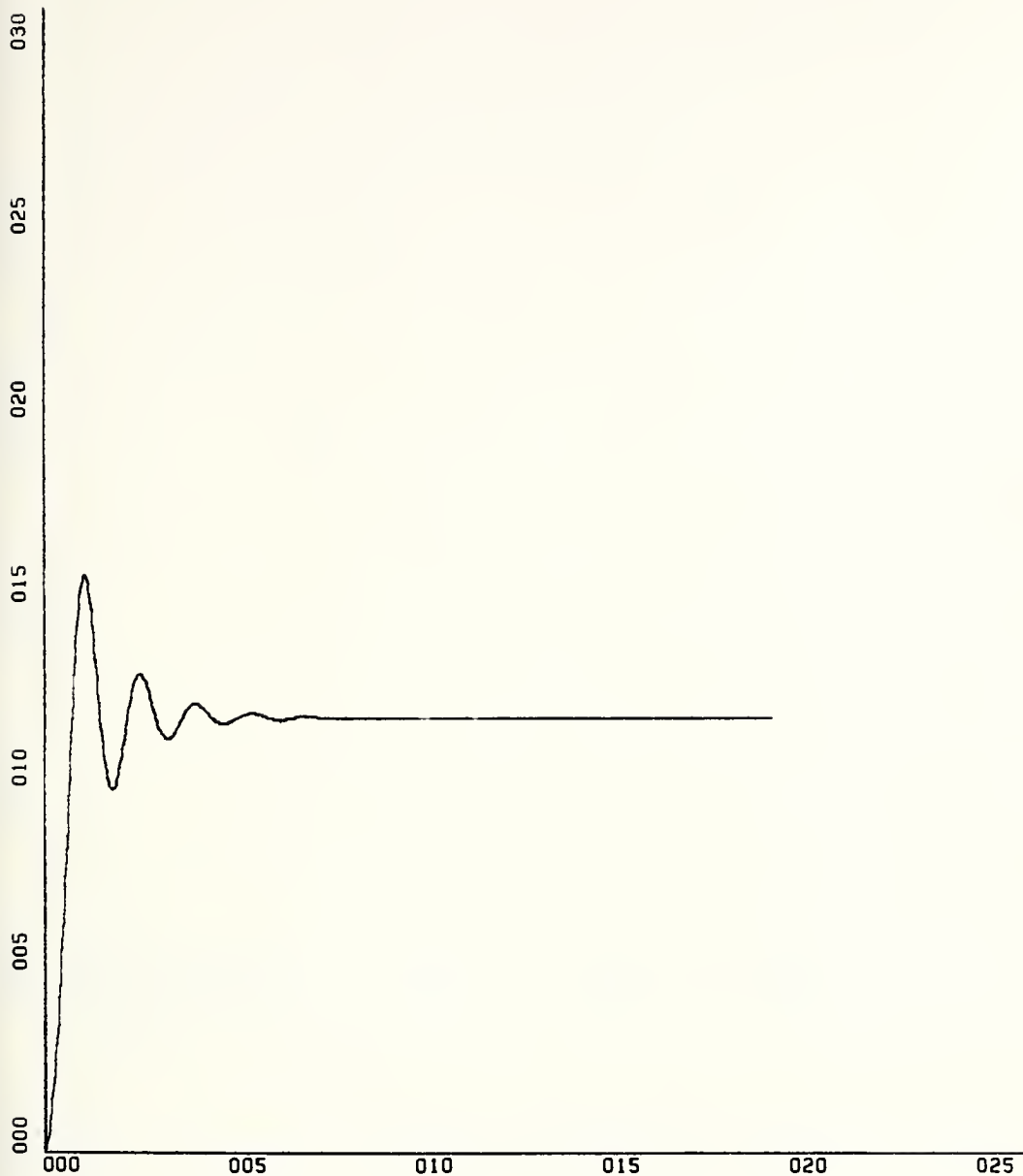Figure 18. 60 DOF roll rate plot, $\delta_r = 10°$
20 knot speed
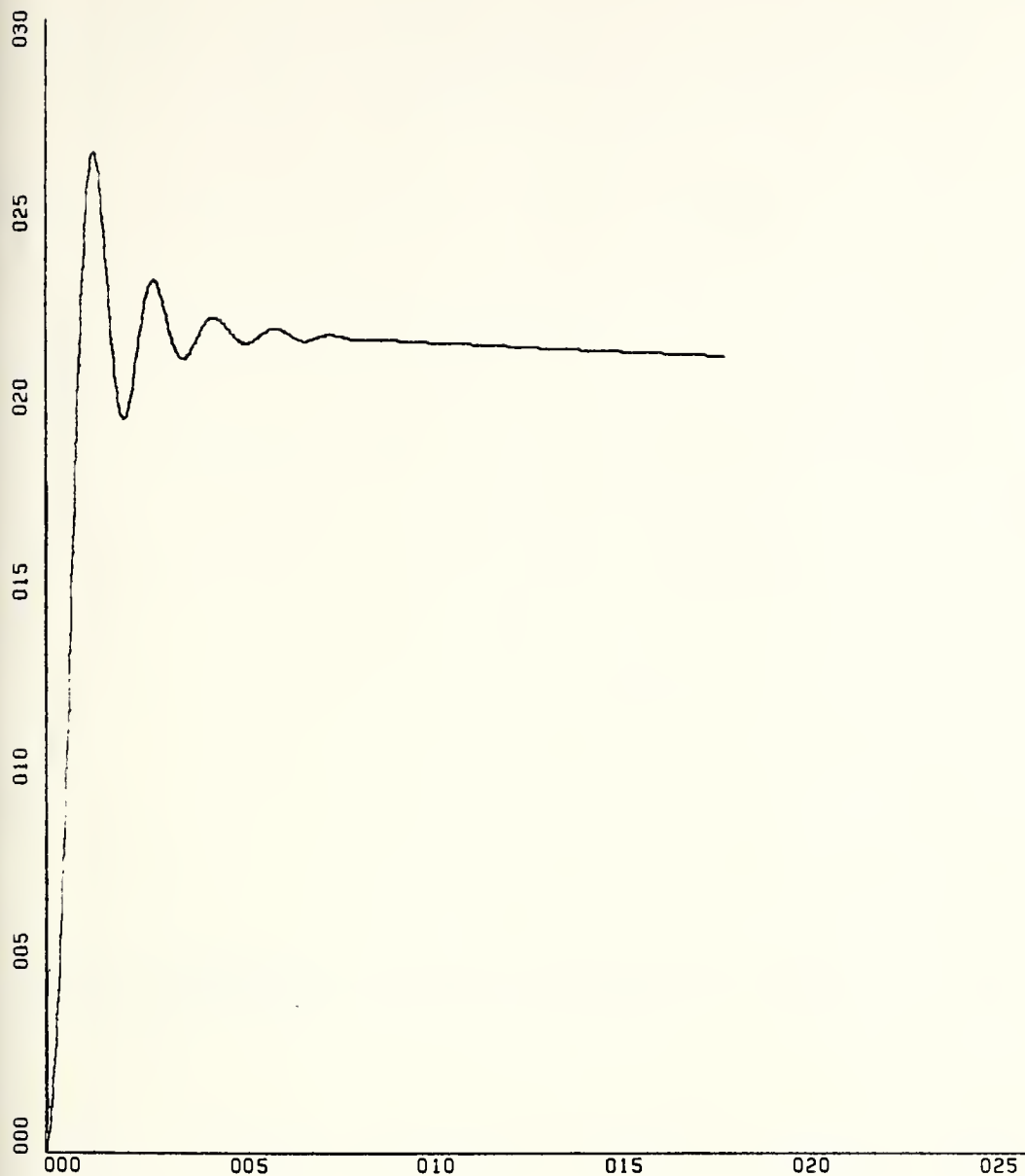
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
XR-3 20 KNOTS SPEED RD=15
PLOT IS ROLL ANGLE

Figure 19. 6 DOF roll angle plot, δ_r = 15°
20 knot speed

X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
XR-3 20 KNOTS SPEED RD=15
PLOT IS ROLL RATE

Figure 20.   6 DOF roll rate plot; δ_r = 15°
              20 knot speed

Figure 21. Linear 5 DOF plenum pressure transient

PLOT IS DRAFT
XR-3 30 KNOTS SPEED
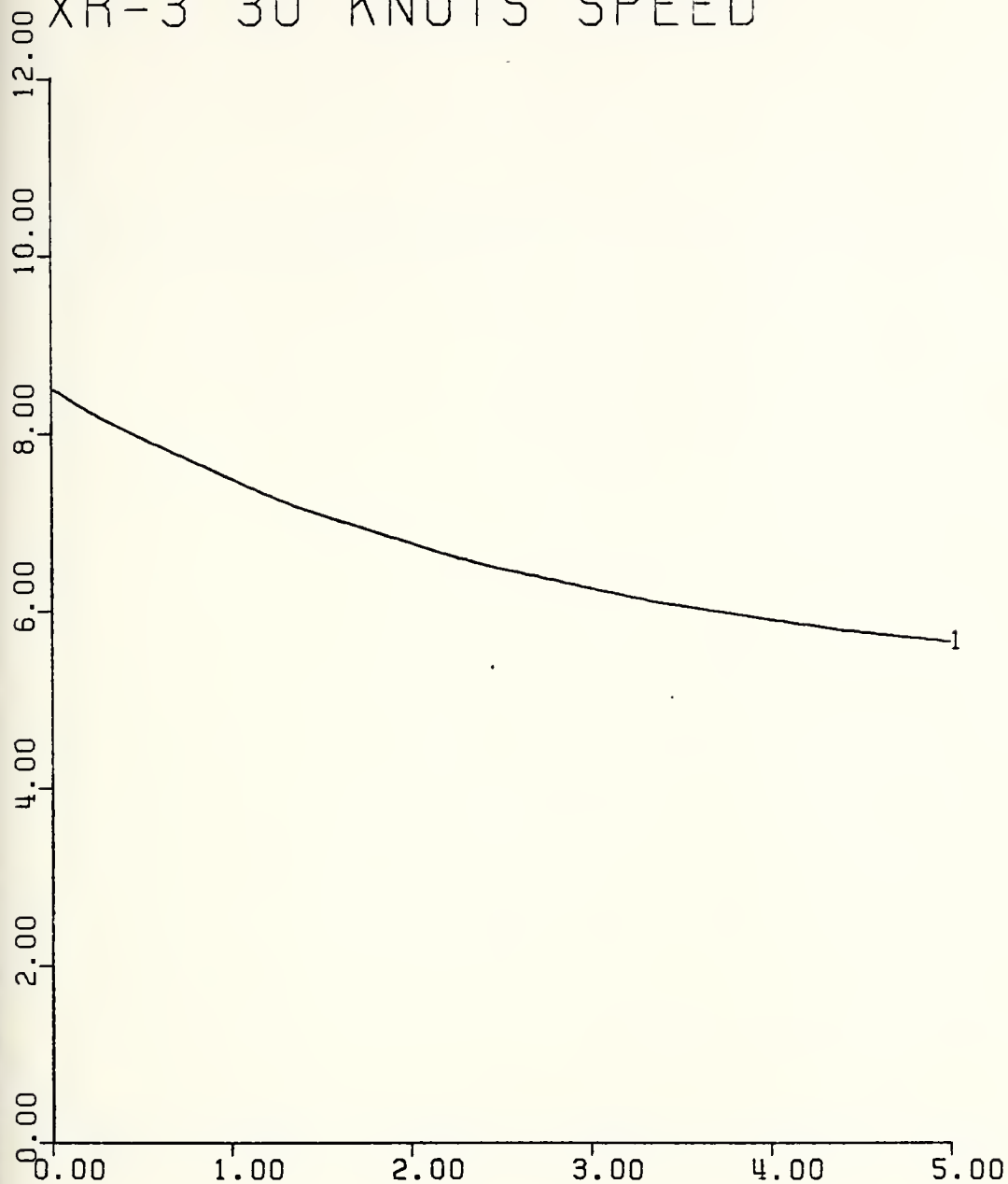
XSCALE= 1.00   UNITS/INCH RUN NO. 1
YSCALE= 2.00   UNITS/INCH PLOT NO. 2

Figure 22. Linear 5 DOF draft transient
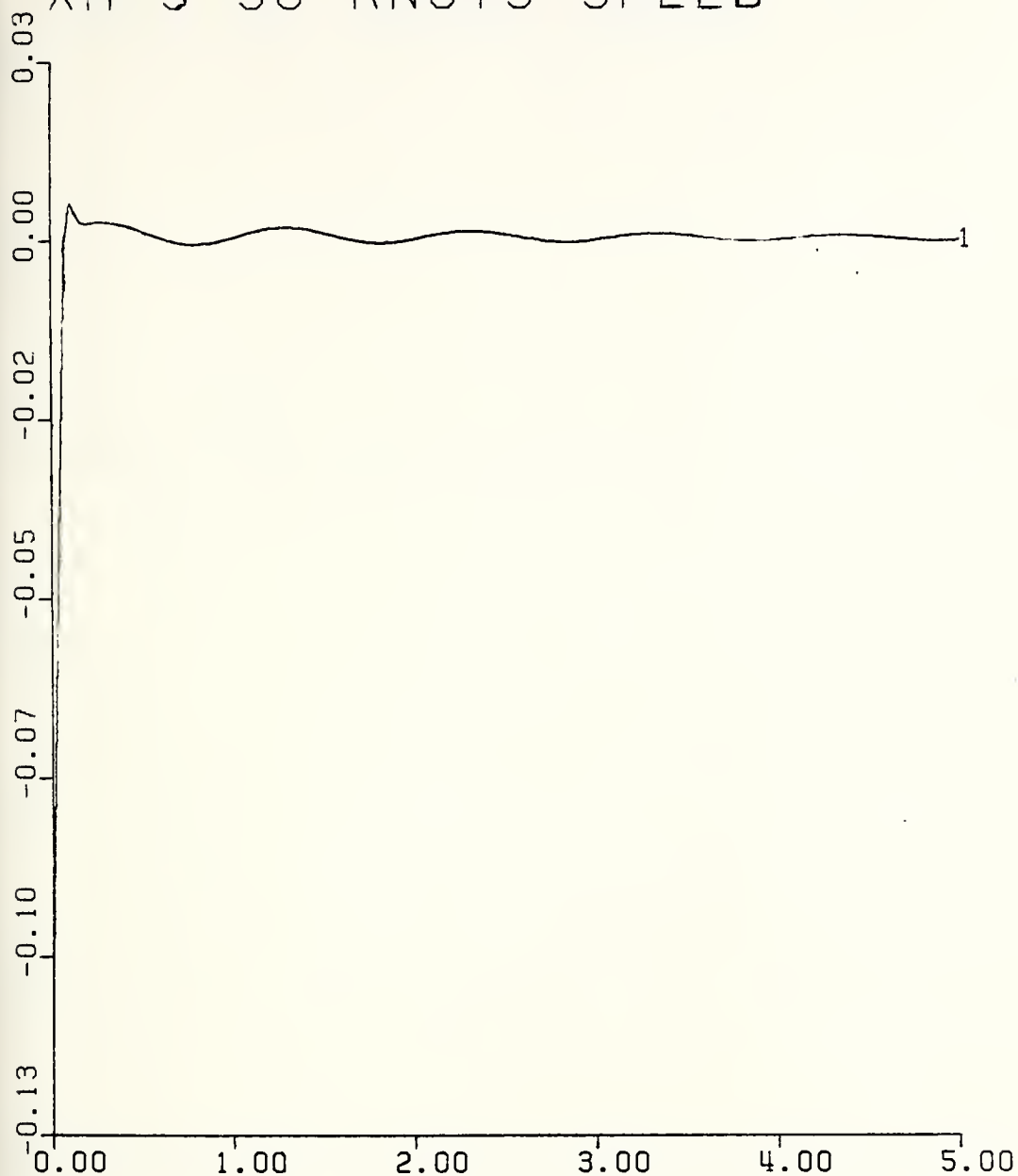
Figure 23. Linear 5 DOF C.G. acceleration

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PLØT IS PITCH ANGLE
XR-3 30 KNØTS SPEED
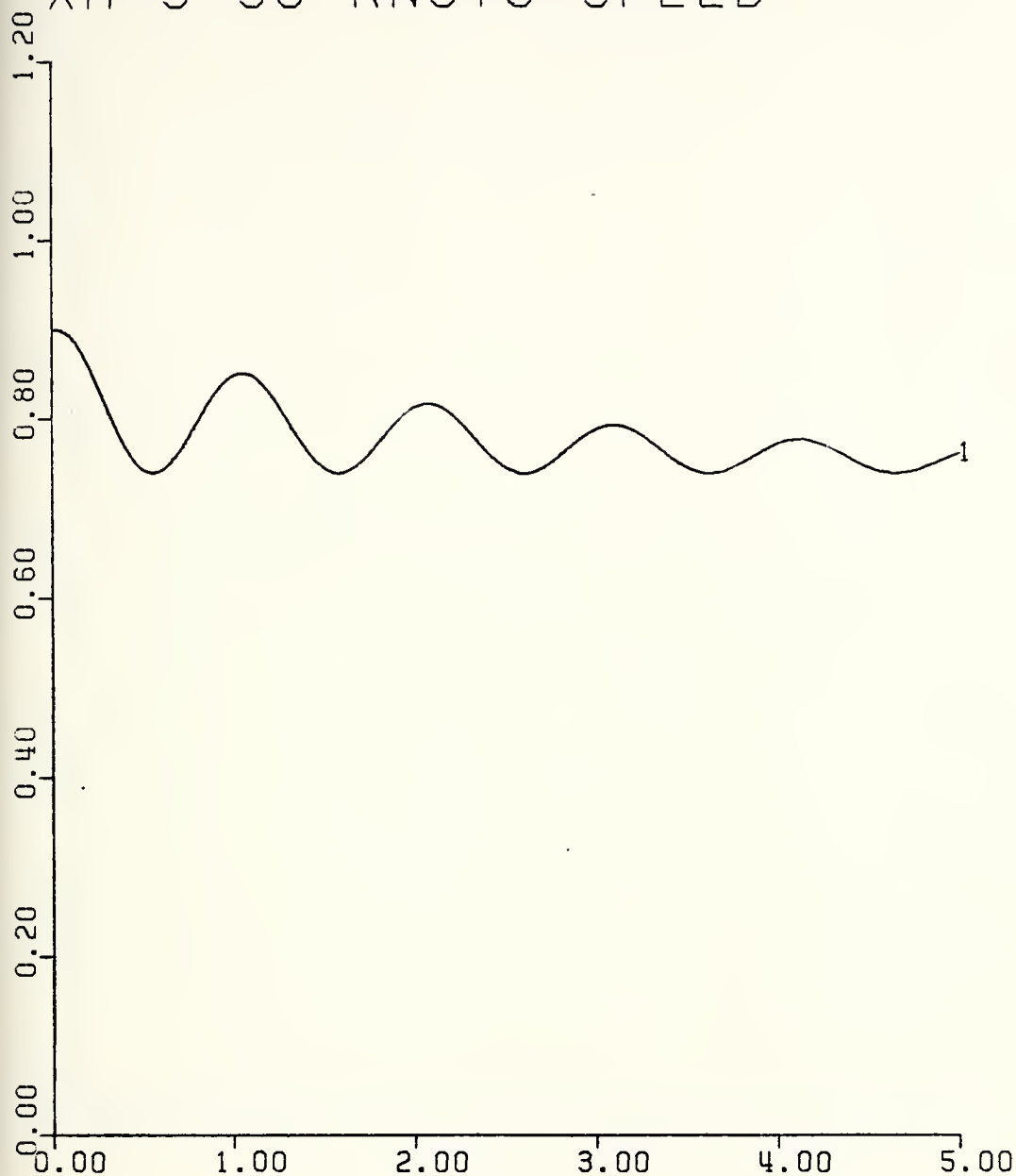
XSCALE= 1.00   UNITS/INCH RUN   NØ. 1
YSCALE= 0.20   UNITS/INCH PLØT NØ. 4

Figure 24. Linear 5 DOF pitch angle transient

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Figure 25. Linear 3 DOF roll angle plot, $\delta_r = 3°$
30 knot speed

Figure 26.   Linear 3 DOF roll rate plot, $\delta_r = 3°$
             30 knot speed

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Figure 27. Linear 3 DOF roll angle plot, δ_r = 5°
30 knot speed

Figure 28. Linear 3 DOF roll rate plot, $\delta_r = 5°$
30 knot speed

PLOT IS ROLL ANGLE
XR-3 20 KNOTS SPEED RD=10
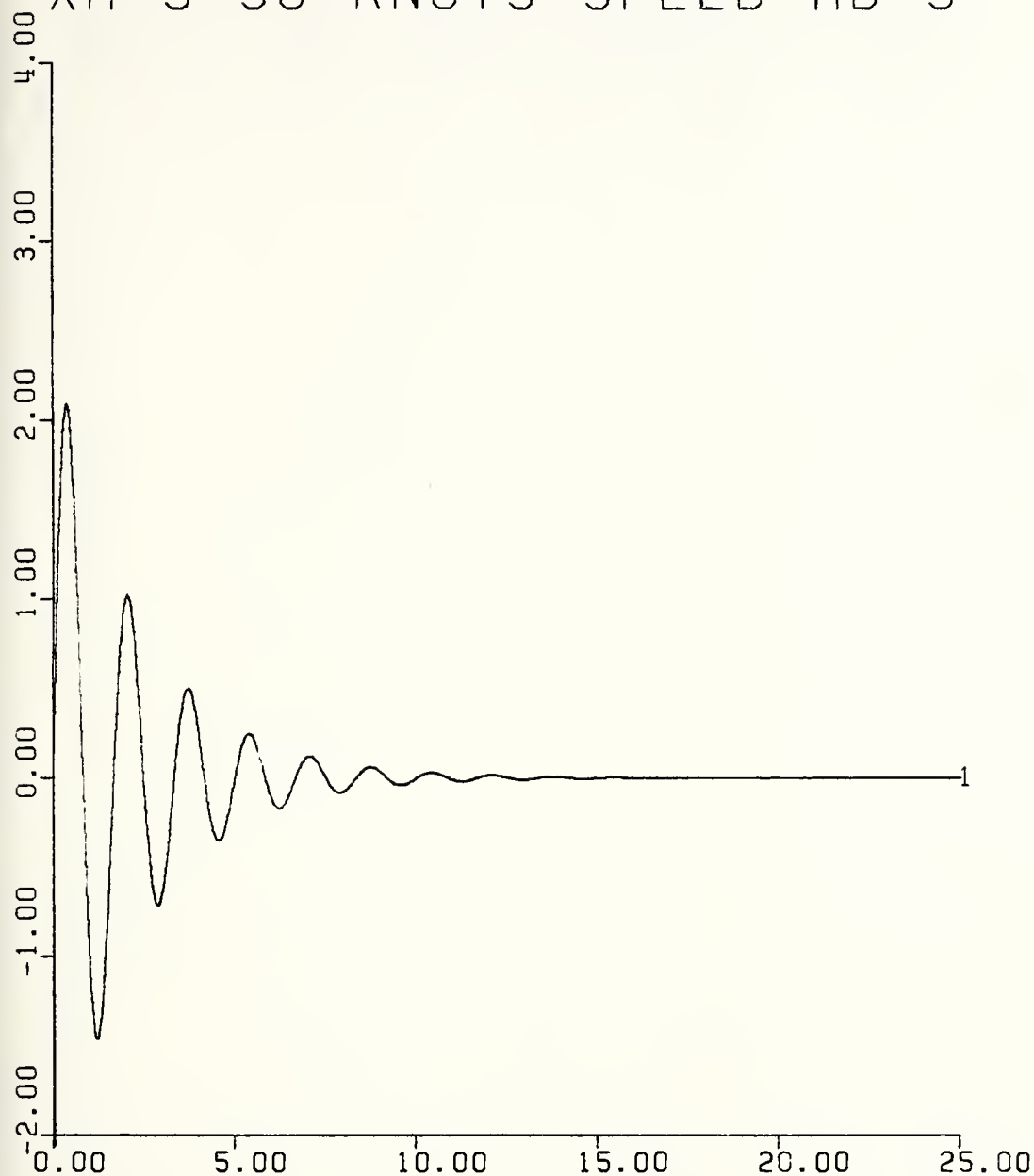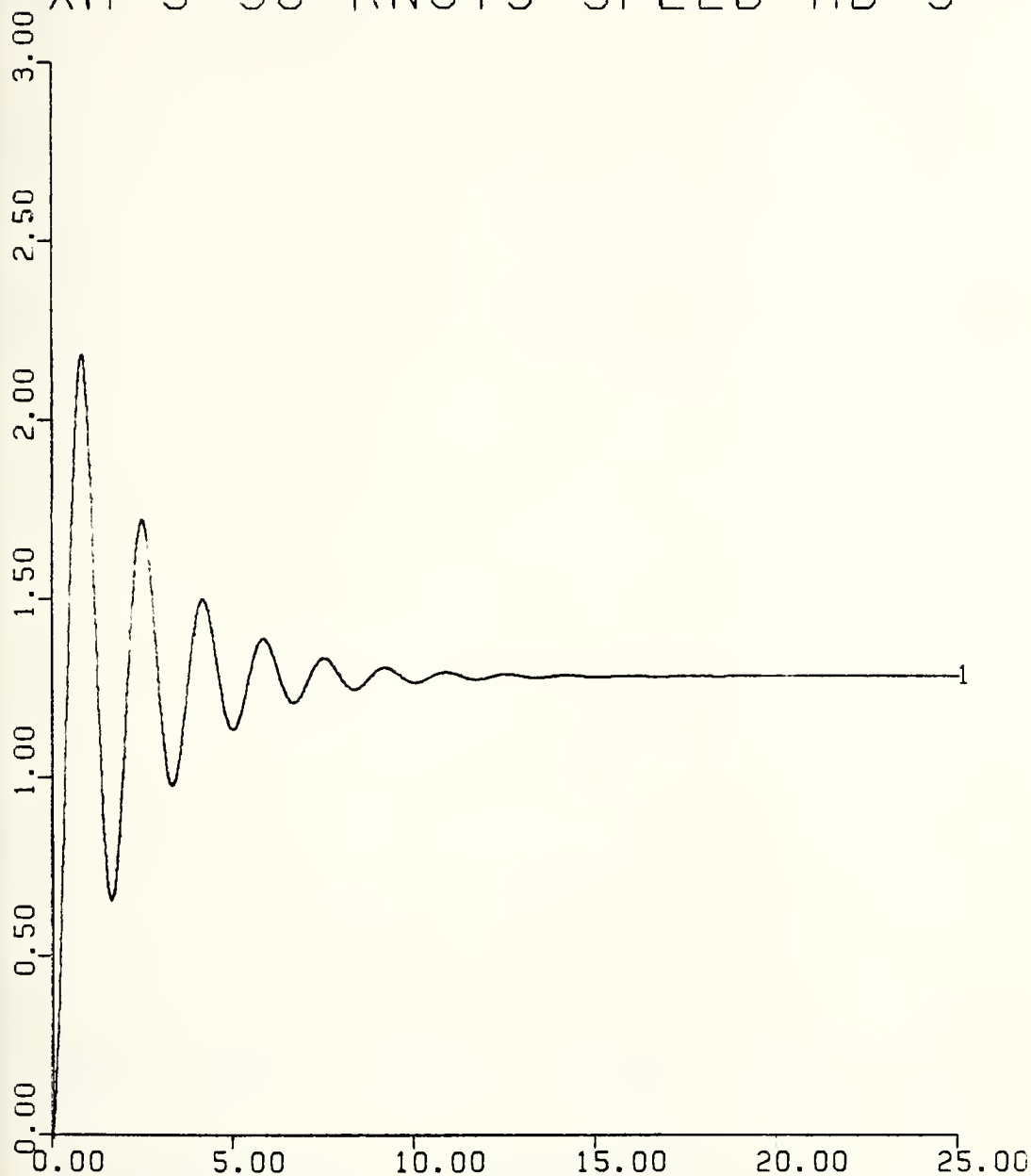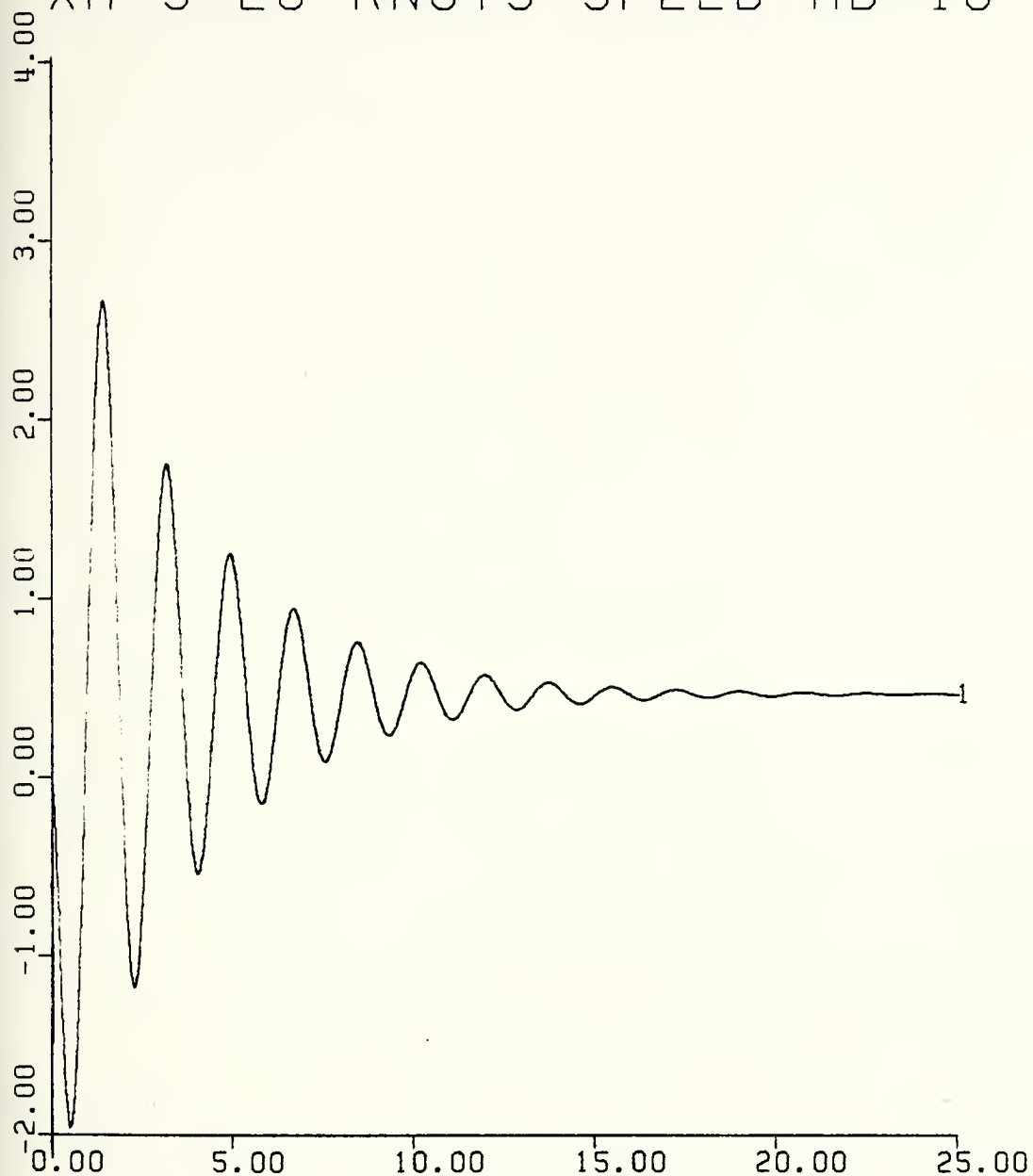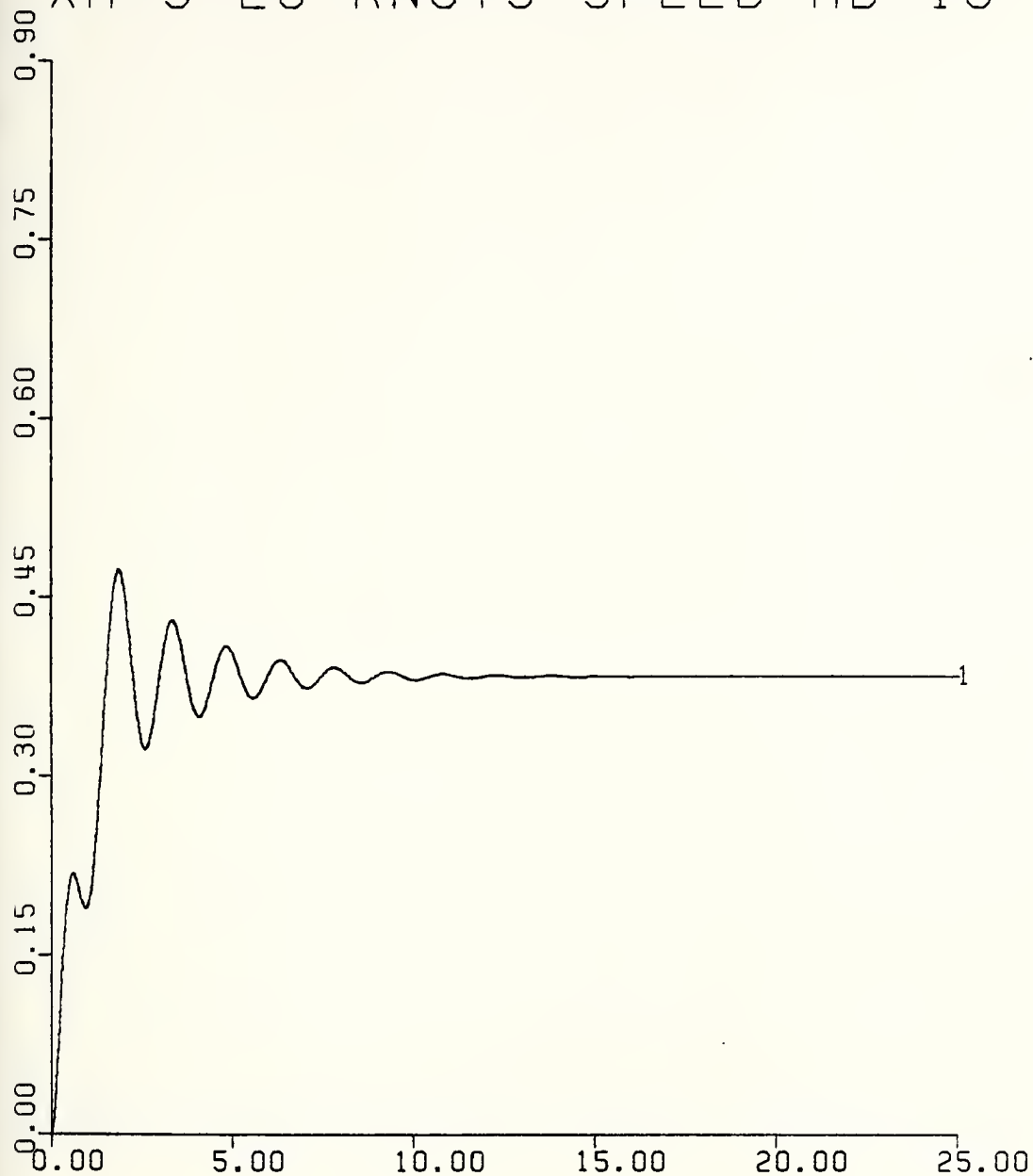
XSCALE= 5.00   UNITS/INCH   RUN   NO. 1
YSCALE= 1.00   UNITS/INCH   PLOT NO. 1

Figure 29.   Linear 5 DOF roll angle plot, δ_r = 10°
             20 knot speed (omitting I_{xz} term)

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PLØT IS RØLL ANGLE
XR-3 20 KNØTS SPEED RD=5
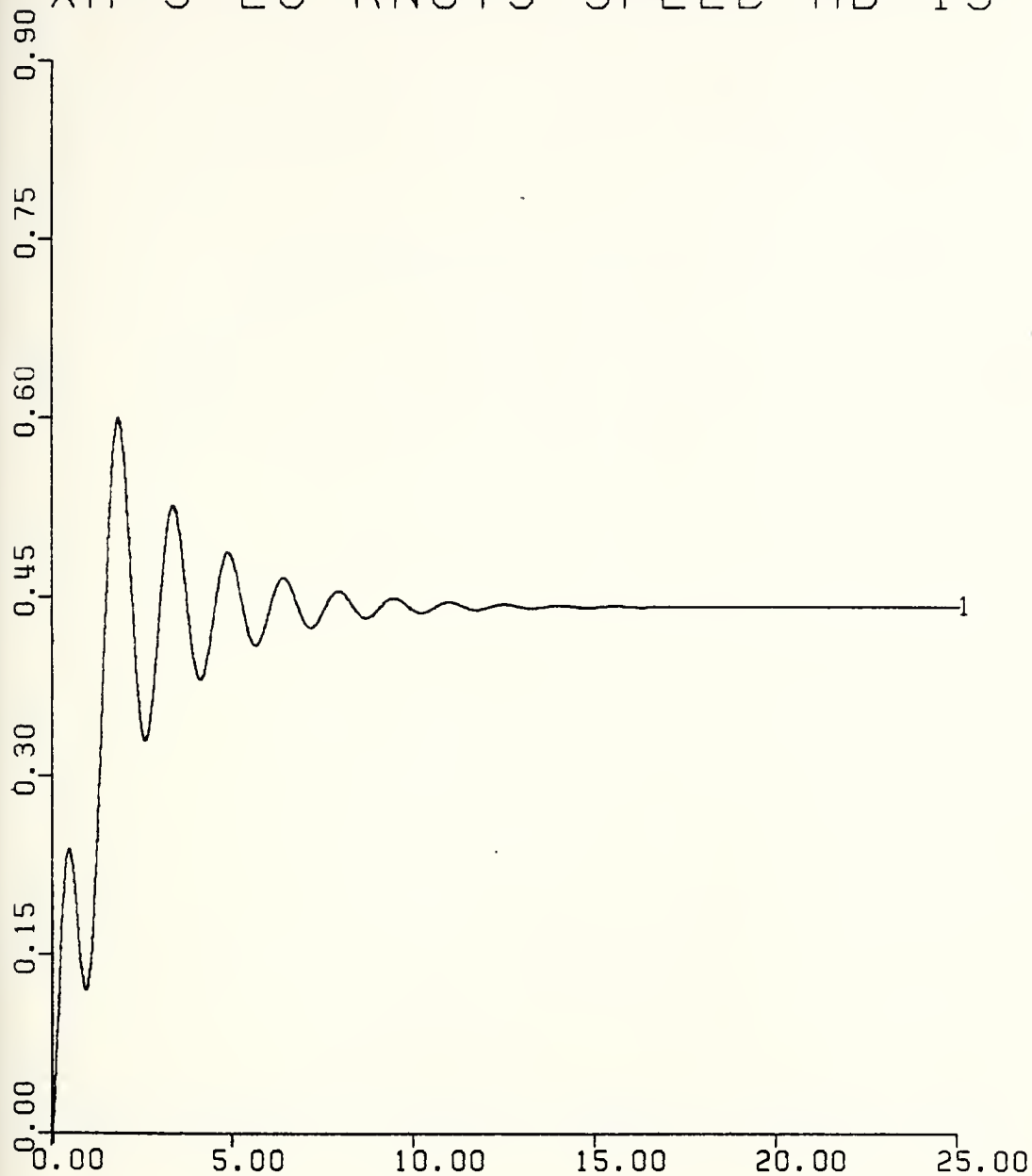
XSCALE= 5.00   UNITS/INCH RUN NO. 1
YSCALE= 0.07   UNITS/INCH PLØT NO. 1

Figure 30.   Linear 5 DOF roll angle plot, $\delta_r = 5°$
20 knot speed

Figure 31.   Linear 5 DOF roll angle plot, $\delta_r = 10°$
20 knot speed

Figure 32. Linear 5 DOF roll angle plot, $\delta_r = 15°$ 20 knot speed

PLØT IS LATERAL VELØCITY
XR-3 20 KNØTS SPEED RD=10
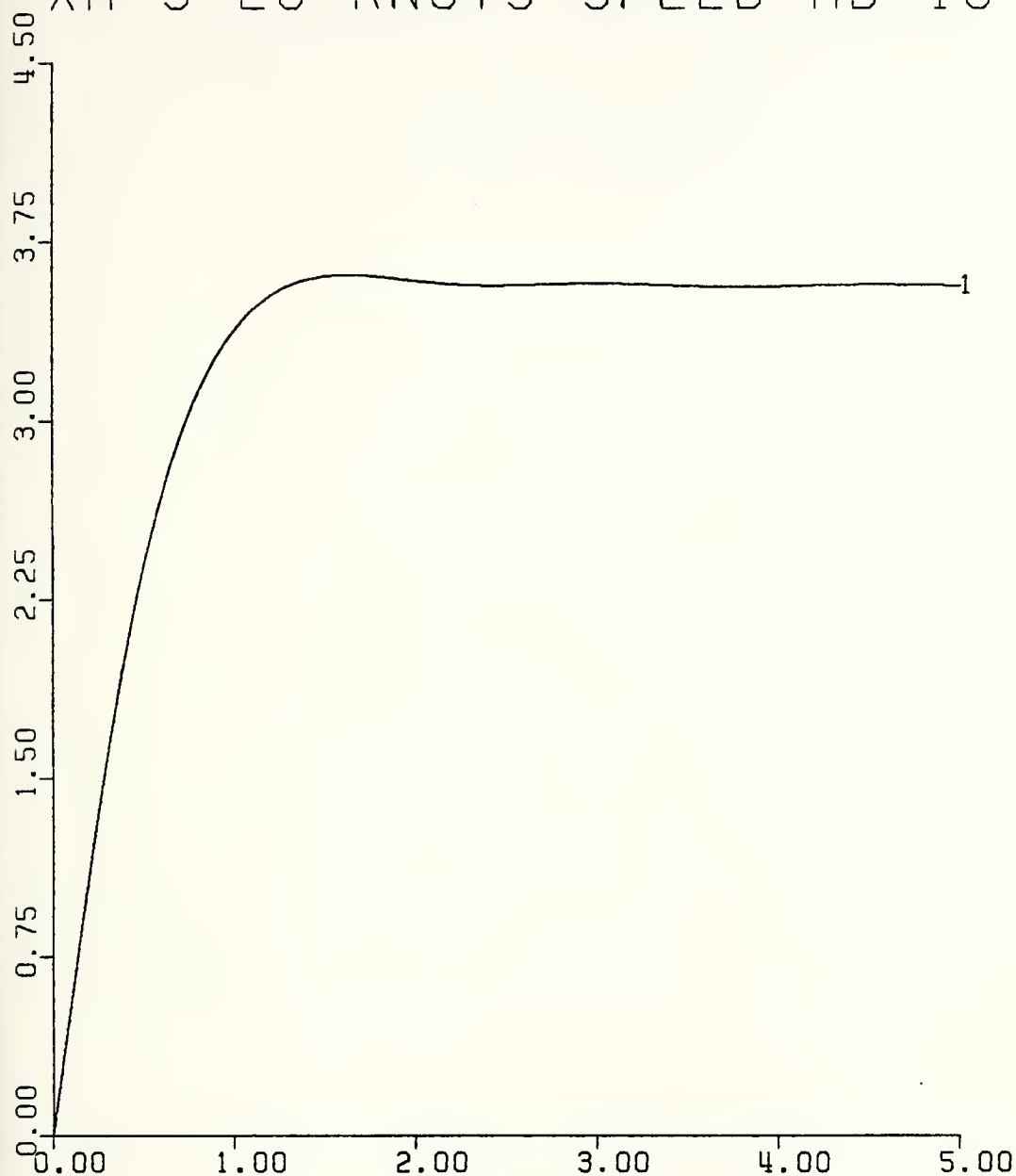
XSCALE= 1.00   UNITS/INCH RUN NØ. 1
YSCALE= 0.75   UNITS/INCH PLØT NØ. 2

Figure 33. Linear 5 DOF lateral velocity plot
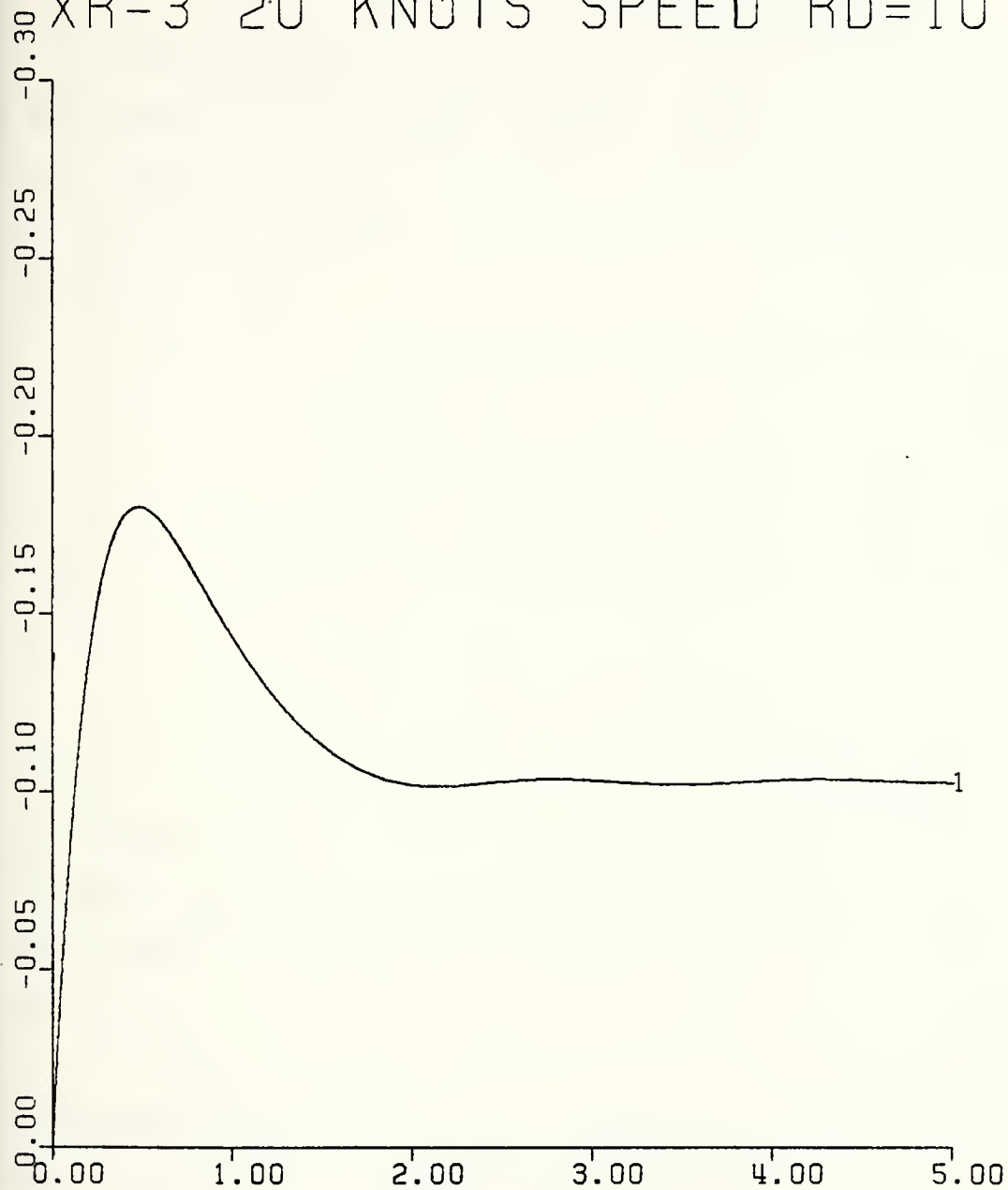
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Figure 34. Linear 5 DOF yaw rate plot

VII.   CONCLUSIONS AND RECOMMENDATIONS

In the preceding sections, the 5 DOF linear XR-3 model was developed, then weight removal response and roll behavior are compared with 6 DOF nonlinear simulations. Also some of the craft sensitivity parameters are investigated for the XR-3 test craft.

The results of this study are summarized and recommendations are made as follows.

1.   The system response is investigated by both a linear model and a 6 DOF nonlinear model by means of sudden weight removal from the C.G. and by sway force disturbance in a turn.

Comparison of results shows that the difference is within 10% for both models. In fact, assuming accuracy in measurements of about 10%, the linearized model gives acceptable results as compared with the nonlinear model. Obviously the linear model simulations take less computer CPU time.

2.   Concerning roll response during the turn maneuver, the product inertia term (I_{xz}) affects transient response such as overshoot, damping, etc. More overshoot and oscillatory response have been observed without I_{xz}. However, this term is found to be -2800. from the 6 DOF program. It is suggested that this number be verified.

3. The importance of deadrise is observed for roll steady state behavior. The XR-3 test craft steady state roll angle depends upon the average deadrise angle of the sidewall. Different average deadrise angles have been simulated by means of the linear model and it is observed that the craft rolls inboard or outboard according to the sidewall deadrise configuration.

The 6 DOF nonlinear model SIDEWALL SUBROUTINE must be modified by including a cross flow drag component deadrise projection (lift force). However a new drag coefficient is needed for this lift component.

4. The aerodynamic effect of the craft contributes about 5% of the total yaw moment.

5. The XR-3 failure mode operation (such as fan failure) can be simulated by using either the linear or nonlinear model. But, the nonlinear model is preferable for failure mode simulations, since it includes sidewall and stern seal leakage configurations.

```
        XR-3  5 D.O.F.  LINEAR  MODEL

***   INTEG RKSFX
      INCON A=0.0
      INTGER NPLCT
      CONSTAN NPLOT=1
      INITIAL
***   PHYSICAL CONSTANTS

      G=32.2                                    SES000120
      GAMMA=1.4                                 SES000130
      PA=2116.0                                 SES000140
      PI=3.141593                               SES000150
      RHO=2.0                                   SES000160
      RHOA=0.002378                             SES000170

***   CRAFT DIMENSIONS

      ZS=2.5                                    SES00440
      BUBHGT=1.915                              SES00420
      XCPC=0.4634
      XS=10.05
      YSW=5...
      ZSW=2.3
      PLAREA=4.23                               SES000210
      PLCOEF=6.78                               SES000220
      PLCOSW=1.28                               SES000230
      DR=70.                                    SES000240
      L=20.                                     SES000250
      WIDT=10.0                                 SES000260
      AL1=10.3                                  SES000270
      AL2=5.6                                   SES000280
      AL3=11.2                                  SES000290
      AL4=8.26                                  SES000300
      AL5=AL1/2.0                               SES000310
      AL6=AL2/2.0                               SES000320
      AL7=4.27                                  SES000330
      AL8=17.1                                  SES000340
      DR1=61.5                                  SES000350
      DR2=68.2                                  SES000360
      WS10=0.2
      WS20=0.52
      CN=0.9
      ALPR=15.72
      ALPWL=15.65
```

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```
      ALDIFF=ALPWL-ALPR                                    SES00370
      ABDIFF=ALDIFF*WIDTH                                  SES00380
      ABW=ALPWL*WIDTH                                      SES00400
      ABR=ALPR*WIDTH                                       SES00410
      VN=((ALPR+ALPWL)/2.0)*BUBHGT*WIDTH                   SES00430
      GIO=35.0                                             SES00450
      EN=5.0                                               SES00460
      AIYY=9520.
      AIXX=2870.
      IR=7844.3
      I=-8044.5
      IK=2129.
      A33S=0.7C88

C     ANGULAR CONVERSION FACTORS AND CONVERSIONS

      RADEG=360.0/(2.0*PI)                                 SES00530
      DEGRAD=(2.0*PI)/360.0                                SES00540
      CR1=CR1*DEGRAD                                       SES00550
      CR2=CR2*DEGRAD                                       SES00560
      BETA=CR*DEGRAD
      CR=BETA

C     INPUT FINAL OPERATING POINT

      V=23.73
      PBBAR=24.8
      THETA=0.26
      ALD=5.34
      VL=3.6
      R=-0.1
      PHI=0.47
      PHD=0.C
      W=6722.
      WF=6050.

C     RUDDER ORDER INPUT

      RUDANG=10.

C     VELOCITY REDUCTION
      V=SQRT(V**2-VL**2)

      AMASS=W F/G                                          SES01480
      ALC=ALC/12.0                                         SES00820
      THETA=THETA*DEGRAD                                   SES0083C
    5 RUDANG=RUDANG*DEGRAD
```

```
INPUT INITIAL OPERATING POINT

PHI=0.0
THI=0.5
PBI=24.5
LDI=8.5
FYP=18E
PHI=PHI*DEGRAD

CALCULATE INTERMEDIATE VARIABLES AND CONVERSIONS

ALC1=ALC-AL5*THETA                                                    SES00850
ALD2=ALD+AL6*THETA                                                    SES00860
WS1=WS10+(ALD1/(2.*TAN(DR1)))
WS2=WS20+(ALD2/(2.*TAN(DR2)))
AK1=2.0*RHO*G*AL1                                                     SES00890
AK2=2.0*RHC*G*AL2                                                     SES00900
AK3=WICTH/(SIN(31*DEGRAD))                                            SES00910
AK4=WICTH/(SIN(32*DEGRAD))                                            SES00920
XSEAL1=(ALC-AL3*THETA)/SIN(31.0*DEGRAD)                               SES00930
XSEAL2=(ALD+AL4*THETA)/SIN(32.0*DEGRAD)                               SES00940
ASEAL1=WICTH*XSEAL1                                                   SES00950
ASEAL2=WIDTH*XSEAL2                                                   SES00960
PLC=RHC*PLAREA*V**2*PI*PLCOEF
XCPC=RALFWL/2.0-(119.6/12.0)
XCP=XCPC+(ALDIFF*ALD/BUBHGT)/2.0+XCPC
AB1=(ABW-ABR)*(ALD/BUBHGT))/COS(PHI)
VB=VN-AB1*ALD
PB=PA+FBEAR
AMB=RHCA*VB*(PB/PA)**(1.0/GAMMA)
QIN=EN*(CIO-PBBAR)
AL=QIN/(CA*SQRT(2.0*PBBAR/RHOA))
BC2=PI/E.*RHO*(AL1+AL2)*ALD**2*(COTAN(BETA))**2
CSS1=ALC+XS*THETA
CSS1=ALC+YSW*PHI+XS*THETA
CSS2=ALC-YSW*PHI+XS*THETA
BL2=(WS20+WIDTH)/2.+ALD2/(2.*TAN(DR2))
BW1=ALD1/TAN(DR1)+WS10
BW2=ALD2/TAN(DR2)+WS20
BS=WS20+(ALD+XS*THETA)/TAN(DR2)
A22S=(R+0*0.2*PI*(DSS1**2+DSS2**2)/2.)                                SES00390
DD2=0.5*RHC*CDSW*L                                                    SES00990
C3=A22S*YSW**2*V
VREL=VL-XS*R-(ZS-ALD/2.)*PHD                                         SES01020
                                                                      SES01040
                                                                      SES01050
```

***   ***

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```
      OUTPUT FORCES,MOMENTS, AND RESIDUALS AT FINAL OPER POINT

      HPRES=-AB*PBBAR                                        SES01140
      PPRES=-HPRES*XCP                                       SES01150
      HBF=-AK1*ALD1*WS1                                      SES01160
      HBA=-AK2*ALD2*WS2                                      SES01170
      HSF=-(PBBAR*ASEAL1
      HSA=-(PBBAR+2.0)*ASEAL2                                SES01230
      HPF=-HFLC**THETA                                       SES01240
      HPA=-PLC**THETA                                        SES01260
      PBF=-AL5*HBF                                           SES01270
      PBA=-AL6**HBA                                          SES01280
      PLSF=AL3-XSEAL1/2.0
      PLSA=AL4+XSEAL2/2.0                                    SES0129C
      PSF=-HSF*FLSF
      PPLAN=-2.*PLC*PLARM*THETA
      PSA=HSA*FLSA
      RPRES=-HPRES*(ZS-ALD)*PHI
      RBF=-AK1*EL1**2*BW1*PHI
      RBA=-AK2**2*BW2*PHI
      RSF=-(WIDTH/2.52)**3*XSEAL1*RHO*G*PHI                  SES01310
      RSA=-(WIDTH/2.52)**3*XSEAL2*RHO*G*PHI                  SES01320
      RES1=WA+LBF+HBA+HSF+HSA+HFF+HPA+HPRES                  SES01330
      RES2=PBF+PBA+PSF+PSA+PPLAN+PPRES                       SES01340
      RES3=RFFES+RBF+RBA+RSF+RSA
      ACCCEL=RES1/AMASS
      PACCCEL=RES2/AIYY
      RACCEL=RES3/AIXX
      WSTEP=F-J

      SIN31=SIN(31.0*DEGRAC)                                 SES01750
      SIN32=SIN(32.0*DEGRAC)                                 SES01760

      COMPUTE SENSITIVITY COEFFICIENTS

      DERIVATIVES OF PBBAR AND MB

      DPBDZ=GAMMA*(AB1-ABCIFF*ALD/BUBHGT)*PB/VB              SES01810
      CPBMB=GAMMA*PB/AMB                                     SES01820
      DMBPB=-RHOA*(EN+CN*AL/(RHOA*SQRT(2.0*PBBAR/RHOA)))     SES01830
      DMBZ=DPBPB*DPBDZ                                       SES01840
      CMBME=ENBFB*DPBMB

      DERIVATIVES OF HEAVE FORCES W/RESPECT TO Z
```

***   *   *******   ***

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```
CHEFZ=-AK1*((ALD-AL5*THETA)/TAN(DR1)+WS10)                            SES01880
CHBAZ=-AK2*((ALD+AL6*THETA)/TAN(DR2)+WS20)                            SES01890
DHBZZ=(CHBFZ+DHBAZ)                                                   SES01900
CHSFZ=-AK3*PBBAR-AK3*(ALD-AL3*THETA)*DPBDZ                            SES01910
DPBZZ=PBBAR*ABDIFF/BUBHGT                                             SES01920
DHSAZ=-AK4*(PBBAR+2.)-AK4*(ALD+AL4*THETA)*DPBDZ                       SES01930
DHSZZ=DHSFZ+DHSAZ
DHPBZ=-AE*DPBDZ+DPBZ
CZZ=(CHBZ+DHSZ+DHPBZ)/AMASS

DERIVATIVES OF HEAVE FORCES W/RESPECT TO THETA

DHBFTH=AK1*(ALS*(ALD-AL5*THETA)/TAN(DR1)+AL5*WS10)                    SES02010
CHBATH=-AK2*(AL6*(ALD+AL6*THETA)/TAN(DR2)+AL6*WS20)                   SES02020
DHSFTH=AK3*AL3*PBBAR
CHSATH=-AK4*AL4*(PBBAR+2.0)                                           SES02050
DSWTH=-2.*V**2*(A33S+THETA*(2.*RHO*PI*BS*XS/TAN(DR2))/8.)             SES02060
CHPFTH=-FLC+0.5*DSWTH
DHPATH=-FLC+0.5*DSWTH                                                 SES02080
DHBTH=CHBFTH+DHBATH
CHSTH=CHSFTH+DHSATH
DHPTH=CHPFTH+DHPATH                                                   SES02120
CZTH=(CHBTH+DHSTH+DHPTH)/AMASS                                        SES02130

DERIVATIVE OF HEAVE FORCE W/RESPECT TO MB                             SES02140

DHPBMB=-AE*DPBMB                                                      SES02150
DHSFMB=-ASEAL1*DPBMB
DHSAMB=-ASEAL2*DPBMB
DZMB=(CHPBMB+DHSFMB+DHSAMB)/AMASS

DPCP=-2.*(BC2+A33S*XS)*V
DZDP=DFCP/AMASS

DERIVATIVES OF HEAVE FORCES W/R TO PHI                                SES02190

CZPH=0.0                                                              SES02200

DERIVATIVES OF PITCH MOMENTS W/RESPECT TO THETA                       SES02210

DPBFTH=-AL5*DHBFTH
DPBATH=AL6*CHBATH
CPBTH=CFBFTH+DPBATH                                                   SES02250
DPPLTH=-2.*PLC*PLARM+DSWTH*XS
DPSFTH=-PBBAR*(PLSF*AL3*WIDTH/SIN31-ASEAL1*AL3/(2.*SIN31))
DPSATH=(PBBAR+2.)*(PLSF*AL4*WIDTH/SIN32+ASEAL2*AL4/(2.*SIN32))
DPPRTH=C.C
CPSTH=(CFSFTH+DPSATH)
```

```
***          ***          *     ***     ***
```

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```
      DTHTH=(CPBTH+DPPLTH+DPSTH+DPPRTH)/AIYY

C     DERIVATIVES OF PITCH MOMENTS W/R TO THETADOT

      DPDMP=-2.*A33S*XS**2*V                                    SES02290
      DTHDTH=CFDMP/AIYY

C     DERIVATIVES OF PITCH MOMENTS W/RESTECT TO Z

      CPEFZ=-AL5*DHBFZ                                          SES02340
      DPBAZ=AL6*CHBAZ                                           SES02350
      DPPBZ=XCP*(AB*DPBDZ-PBBAR*ABDIFF/BUBHGT)+AB*PBBAR*ALDIFF/...  SES02370
     (2.*BUBHGT)
      DPSFZ=PBBAR*(PLSF*WIDTH/SIN31-ASEAL1/(2.0*SIN31))        SES02390
      DPSAZ=-(PBBAR+2.)*(PLSA*WIDTH/SIN32+ASEAL2/(2.*SIN32))   SES02400
      DPSFPZ=ASEAL1*PLSF*CPBDZ                                 SES02410
      DPSAPZ=-ASEAL2*PLSA*DPBDZ                                SES02420
      CPSFZ=CPSFZ+DPSFPZ                                       SES02430
      DPSAZ=CPSAZ+DPSAPZ                                       SES02440
      DPSZ=(DPSFZ+DPSAZ)
      CPBZ=CPEFZ+DPBAZ
      CPPNZ=0.0
      DTHZ=(CPSZ+DPPBZ+DPPBZ+DPFZ)/AIYY

C     DERIVATIVE OF PITCH MOMENT W/RESPECT TO MB

      DPFBMB=AB*XCP*DPBMB                                      SES02500
      DPSFMB=-FLSF*DHSFMB                                      SES02510
      DPSAMB=FLSA*DHSAMB                                       SES02520
      DTHME=(DPFBMB+DPSFMB+DPSAMB)/AIYY

C     CERIVATIVES OF PITCH MOMENTS W/R TO PHI

      DPPH=0.0

C     RUDDER HYDRODYN.
      RAREA=0.68
      RSPAN=1.21
      XR=-11.175
      ZR=2.708
      RASPR=2.15
      CSR=ALC-XR*THETA
      RCLB=2.*FI*RASPR/(RASPR+3.)
      ENDFAC=1.+DSR/(DSR+RSPAN)
      VH=VL+XR*R-ZR*PHD
      QQ=0.5*FHC*V**2*RAREA
      RDC=2.*CG*ENDFAC*RCLB
```

***

***

***

***   ***

```
      FRD=RDC*RLCANG
      PM=1.0
      IF(VL.LT.0.0) GO TO 10
      PM=-1.
   10 CONTINUE
```

*** DERIVATIVES OF ROLL MOMENTS W/R TO Z

```
      DRSFZ=-(WIDTH/2.28)**3*RHO*G*PHI/SIN31
      DRSAZ=-(WIDTH/2.28)**3*RHO*G*PHI/SIN32
      CRSZZ=CRSFZ+DRSAZ
      DRBFZ=-AK1*PHI*(2.*BL1/(2.*TAN(DR1))+BL1**2/TAN(DR1))
      DRBAZ=-AK2*PHI*(2.*BL2*BW2/(2.*TAN(DR2))+BL2**2/TAN(DR2))
      CREZZ=CRBFZ+CRBAZ
      DRPRZ=-PHI*(AB*PBBAR+(ZS-ALD)*DHPBZ)
      CFYDZ=FN*C1*VREL**2
      DRPLZ=CFYCZ*(COS(DR)*YSW-SIN(DR)*ZSW)
      DRZ=(DRSZ+DRBZ+DRPRZ+DRPLZ)/AIXX
```

*** DERIVATIVES OF ROLL MOMENTS W/R TO THETA

```
      CRSFTH=(WIDTH/2.28)**3*RHO*G*PHI*(AL3/SIN31)
      DRSATH=-(WIDTH/2.28)**3*RHO*G*PHI*(AL4/SIN32)
      CRSTH=CRSFTH+DRSATH
      DRBFTH=AK1*PHI*(2.*BL1*BW1/(2.*TAN(DR1))+BL1**2*AL5/TAN(DR1))
      DRBATH=-AK2*PHI*(2.*BL2*BW2*AL6/(2.*TAN(DR2))+BL2**2*AL6/TAN(DR2))
      CRETH=CRBFTH+DRBATH
      DRFTH=0.0
      DRTH=(CRSTH+DRBTH+DRPTH)/AIXX
```

*** DERIVATIVES OF ROLL MOMENTS W/R TO MB

```
      DRPRMB=AE*(ZS-ALD)*PHI*DPBMB
      DRMB=DRFRMB/AIXX
```

*** CERIVATIVES OF ROLL MOMENTS W/R TO PHI

```
      DRSFPH=-(WIDTH/2.28)**3*XSEAL1*RHO*G
      CRSAPH=-(WICTH/2.28)**3*XSEAL2*RHO*G
      CRSPH=CRSFPH+DRSAPH
      CRBAFH=-AK1*BL2**2*BW1
      CRBAFH=-AK2*BL2**2*BW2
      CRBPH=CREFPH+DRBAPH
      CRPRPH=PEBAR*(ZS-ALD)*AB1
      CFYDPH=-FN*D1*VREL**2*PM*YSW
      DRPLPH=CFYDPH*(COS(DR)*YSW-SIN(DR)*ZSW)
      CRFH=(CRSFH+DRBPH+DRPRPH+DRPLPH)/AIXX
```

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DERIVATIVES OF ROLL MOMENTS W/R TO PHIDOT

```
**      CFYPH=A22S*V*ZS
        DRD=ALC-FM*YSW*PHI
        CFYDPD=-FM*D1*DRD*2.*VREL*(ZS-ALD/2.)
        CF=DFYCFD+CFYPH
        DRDPH1=-D2+DF.*(COS(DR)*YSW-SIN(DR)*ZSW)-DFYPH*ZS
        CRWAV=-32./PI*YSW**2*BC2
        CRCPHC=CRCPHI+DRWAV
        DRRUPD=-RCC*(ENDFAC/V)*ZR**2
        CRPC=(CRCFD+DRRUPD)/AIXX

ROLL MOMENTS W/R TO YDOT

***     DFYDYD=FM*D1*DRD*2.*VREL
        DRSWYD=(CFYDYD-D3)*(CCS(DR)*YSW-SIN(DR)*ZSW)+D3*ZS
        DRUDYD=RCC*(ENDFAC/V)*ZR
        DRYD=(CRSWYD+DRUDYD)/AIXX

ROLL MOMENTS W/R TO R

***     CFYDR=-FM*D1*DRD*2.*VREL*XS
        DRSWR=(CFYDR+D3*XS)*(CCS(DR)*YSW-SIN(DR)*ZSW)-D3*XS*ZS
        DRRUCR=RCC*(ENDFAC/V)*ZR*XR
        CRR=(CFSWF+CRRUDR)/AIXX

SWAY FORCES W/R TO YDOT

***     AMASS=E10./G
        CYRDYC=-CRRUCYD/ZR
        CYSWYC=(CFYDYD-D3)*SIN(DR)-D3
        DYYD=(CYRCYD+DYSWYD)/AMASS

SWAY FORCES W/R TO R

**      DYRDR=-CRRLDR/ZR
        CYF=-V*AMASS
        DRSWR=(CFYDR+D3*XS)*SIN(CR)+D3*XS
        DYR=(CYRDR+DRSWR+DYF)/AMASS

SWAY FORCES W/R TO PHIDOT

***     DYRCFC=-CRRUPD/ZR
        DYSWPD=(DFYDPD+D3*ZS)*SIN(DR)+D3*ZS
        CYPC=(CYRCPD+DYSWPD)/AMASS

SWAY FORCES W/R TO PHI

***     DYPH=(DFYDPH*SIN(DR))/AMASS
```

```
*        SW1=0.0E3
         SW2=0.0E15
         LAM=0.515
         MLAM=0.4E5
         AVBM=0.4
         CDF=0.0025
         N1=2.*V*A22S*L*MLAM
         N2=-FI/5.*RHO*L*V
         N3=PM*C.5*RHO*CDSW*((ALD+YSW*PHI)+(ALD-YSW*PHI))
         N4=(ALD+YSW*PHI)**2+(ALD-YSW*PHI)**2
         C1=Sw1*L**3*2.
         C2=Sw2*L**2
         XX=-0.5*RHO*CDF*V**2*L

***   YAW MOMENTS W/R TO YDOT

         DNRCYD=CYRCYD*XR
         DNSWYD=N1+N2*N4+N3*(C1*R+2.*C2*VREL)
         DNYD=DNRCYD+DNSWYD

***   YAW MOMENTS W/R TO R

         DNRDR=CYRDR*XR
         DNSWR=-N1*XS+N3*(C1*VL-2.*C2*VREL*XS)
         DNR=CNFCR+DNSWR

***   YAW MOMENTS W/R TO PHIDOT

         DNRDPD=CYRDPD*XR
         CNSWPD=-N1*ZS-N2*N4*ZS-2.*N3*C2*VREL*(ZS-ALD/2.)
         DNFD=CNRCFC+DNSWPD

***   YAW MOMENTS W/R TO PHI

         DNSWPH=2.*N2*(VL-ZS*PHD)*((ALD+YSW*PHI)*YSW-(ALD-YSW*PHI)*YSW)
         CNXPt=-4.*XX*YSW
         DNPH=DNSkPH+DNXPH

**DERIVATIVE
**
         X1=INTGRL(A,X2)
         X2=INTGRL(A,XZ)
         X3=INTGRL(A,X4)
         X4=INTGRL(A,XP)
         X5=INTGRL(A,XMB)
```

```
X6=INTGRL(A,X7)
X7=INTGRL(A,XROLL)
X8=INTGRL(A,X9)
X9=INTGRL(A,XY)
X10=INTGRL(A,X11)
X11=INTGRL(A,XYAW)
XMB=CMEZ*X1+DMBMB*X5
XP=DTHZ*X1+CTHTH*X3+DTHDTH*X4+DPPH*X6
XZ=DZZ*X1+DZTH*X3+DZMB*X5+DZPH*X6
XY=DYYC*X9+DYR*X11+DYPD*X7+DYPH*X6+(2.*FYP*SIN(RUDANG)+FRD)/AMASS
RR=DRZ*X1+DRTH*X3+DRME*X5+DRPH*X6+DRPD*X7
XR1=(RR+DRYD*X9+DRR*X11)*AIXX-(2.*FYP*SIN(RUDANG)+FRD)*ZR
XN=DNYC*X9+DNR*X11+CNPC*X7+DNPH*X6+(2.*FYP*SIN(RUDANG)+FRD)*XR
XROLL=XR1/IK+XN/I
XYAW=XN/IR+XR1/I

DPB=DPBCZ*X1+DPBMB*X5
FBB=PB1+CFB
LD=LD1+X11*12.
TH=TH1+X3*RADEG
THCC=XF*RADEG
ZDD=XZ/G
PHDD=XRCLL*RADEG
PH=PH1+X6*RADEG
XO=V*TIME
X=XQ*CCS(X10)+X8*SIN(X10)
Y=-XQ*SIN(X10)+X8*CCS(X10)
YAWRT=X11
YDOT=X5
```

```
*SAMPLE
PREPAR 0.05,FT,X,Y,YAWRT,YDOT
CONTRL FINTIM=25.,DELT=0.,DELS=0.031
PRINT 0.05,PH,X,Y,YAWRT,YDOT
GRAF TIME,PH
PRPLCT ONLY
      CALL CFWG(1,1,TIME,PH)
      CALL CFWG(2,1,X,Y)
TERMINAL
      CALL ENERW(NPLOT)

END
STOP
//PLCT SYSIN DD *
PLOT IS RCLL ANGLE
XR-3 20 KNCTS SPEED RD=10     0.15     5.0     6.0
0.0    5.0    0.0
PLCT IS Y VS. X CISPLACEMENT
XR-3 20 KNCTS SPEED RD=10
```
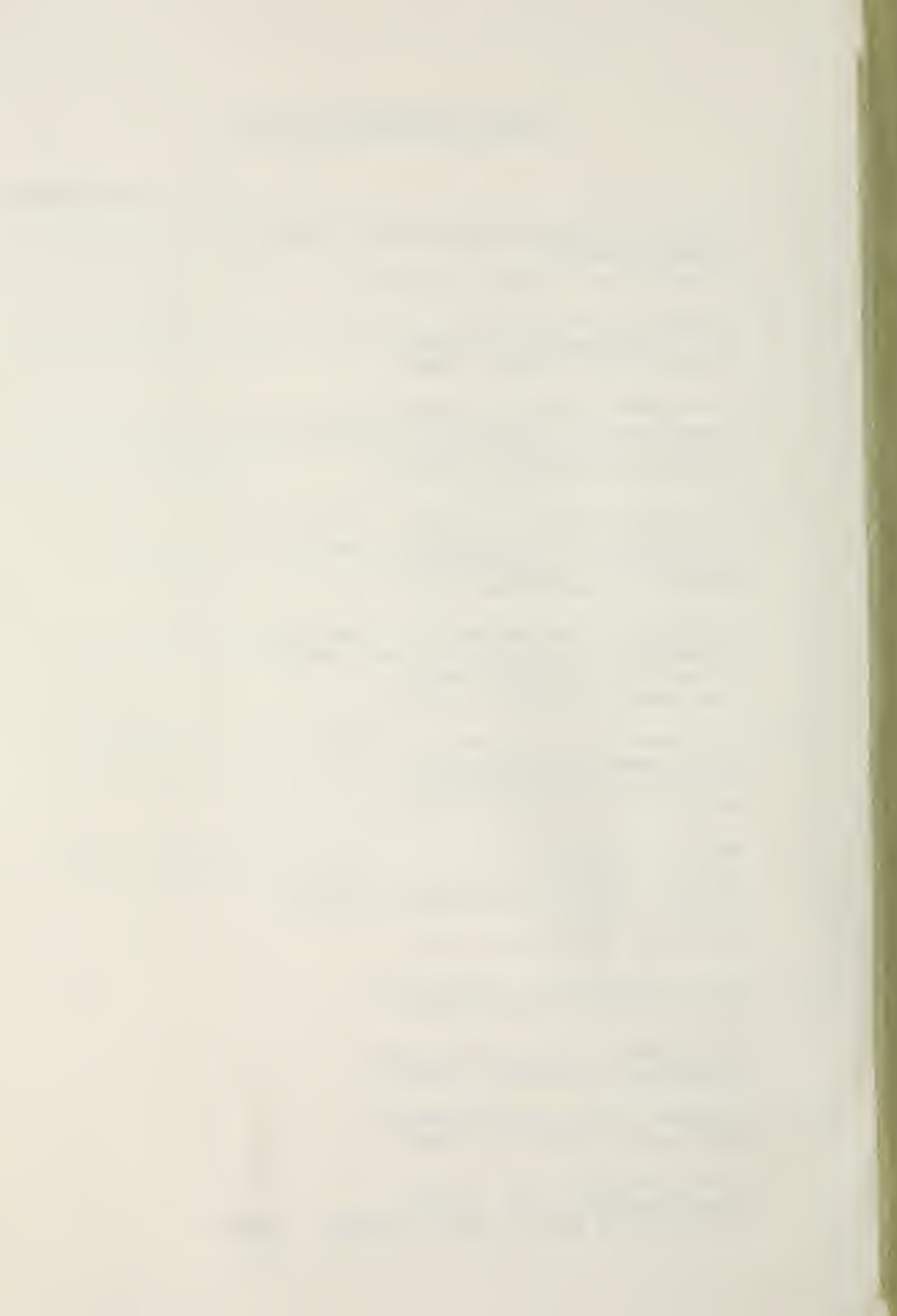
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LIST OF REFERENCES

1. Naval Postgraduate School, <u>Progress Report to SESPO</u>, <u>Pressure Ratio Effect on the Heave Motion Characteristics and Pressure Dynamics of XR-3 for Step Weight Transients</u>, Alex Gerba, Jr., and G.J. Thaler, January 1977.

2. Barnes, L.W., <u>Development and Time Domain Validation of a Low-Order, Constant Speed, Pitch-Heave Model for the XR-3 SES</u>, M.S. Thesis, Naval Postgraduate School, March 1977.

3. Riedel, R.G., <u>Sensitivity Study of the XR-3 Loads and Motions Computer Porgram Sidewall Parameters and Forces on Roll Behavior in Calm Sea and a Comparison to Test-Craft Turn Maneuver Behavior</u>, M.S. Thesis, Naval Postgraduate School, 1977.

4. Department of the Navy, <u>Surface Effect Ship Aero/ Hydrodynamics Technology Design Manual</u>, SES Project PMS-304, Vol. II, February 1976.

5. Department of the Navy, <u>Surface Effect Ship Aero/ Hydrodynamics Technology Design Manual</u>, SES Project PMS-304, Vol. III, February 1976.

6. Menzel, R.F., <u>Study of the Roll and Pitch Transients in Calm Water Using the Simulated Performance of the XR-3 Loads and Motions Program</u>, M.S. Thesis, Naval Postgraduate School, 1975.

7. Leo, D.G., and Boncal, R., <u>XR-3 Surface Effect Ship Test Craft: A Mathematical Model and Simulation Program with Verification</u>, M.S. Thesis, Naval Postgraduate School, December 1973.

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